CAN WE INCREASE CROP YIELD ADOPTING TILE DRAINAGE IN FARGO CLAY SOIL?

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Umesh Acharya

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

SUPERVISORY COMMITTEE:

Dr. Amitava Chatterjee
Chair

Dr. Frank Casey

Dr. Aaron Daigh

Dr. Zhulu Lin

Approved:

March 29, 2018
Date

Frank Casey
Department Chair

ABSTRACT

Subsurface drainage has recently become common for agriculturally productive soils and key to maintain and improve crop production in poorly drained, frigid clay soils. The first study was conducted for four years (2014-17) at Casselton, ND to determine best combination of drainage, tillage and crop rotation for higher corn yield. Our finding suggested corn yield was highest with no drainage, CS and CH combination in years with drought conditions. The second study was conducted for three years (2015-17) to evaluate subsurface drainage spacing (9, 12, and 15m) and depth (0.9 and 1.2m) combination on corn, soybean and sugarbeet yields and residual soil nitrate-nitrogen (NO_3-N) contents. Results indicated that 9 m drain spacing produced highest corn and soybean yield when average across three years in contrast with drain depth that has no effect on corn and soybean yield except for sugarbeet where the 1.2m depth yielded higher than the 0.9m depth.

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Lastly, I would like to thank my family and friends for their continuous support and encouragement throughout my study.

DEDICATION

This work is dedicated to my lovely wife Mrs. Suprabha Khanal (Kanchan) and my parents Mr. Bhesh Raj Acharya and Mrs. Kalika Devi Acharya.

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INTRODUCTION

Artificial subsurface drainage has intensified agricultural production for millennia to manage excess water for trafficability and crop production. Although it has been popular throughout the United States, concerned has been raised about impact of subsurface drainage water on water quality and natural resources (Strock et al., 2011). Water table management for agricultural production has been practiced around globe for thousands of years. The first documented cylindrical drain tiles were manufactured in England in approximately 1810 (Elliott, 1904) and installation in the United Sates occurred near Geneva, New York by John Johnston, a wheat farmer who installed more than 70 miles of drains on his 140 ha farm during his lifetime (King and Lynes, 1946). In many areas of Upper Mid-west of United States, profitable farming is still dependent on artificial drainage. United States Department of Agriculture survey of 1985 on agricultural drainage reported more than 30 % of the cropland in humid north central region including states of Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio and Wisconsin was artificially drained for crop production. According to the 2012 Census of Agriculture, the number of US farms with tile drainage system was 217,931 (14 % of total), covering 48.6 million acres (12.5 % of total) of cropland.

In the Red River Valley (RRV) of North Dakota and northern Minnesota, about 1.8 million ha of soils are poorly drained (USDA-NRCS, 2014). Drainage and flooding are critical problem due to flat topography and dominant poorly drained clay soil (Jin et al., 2008) in RRV. These poorly drained soil of RRV are potentially highly productive but saturated soil conditions and flooding often limit production (Wiersma et al., 2010). Growers in RRV are interested in installing subsurface drainage due to increasing wet climatic periods and the majority of soluble salts in soils within these regions (Sands et al., 2013). Tile drainage removes excess gravitational soil water from agricultural field to decrease length of time of saturated condition; increase length of growing season; an improvement in trafficability for timely planting and harvesting; decrease surface runoff; improve soil aeration and temperature; promotes rapid growth; so that crop productivity is not unduly compromised (Sands, 2001; Jin et al., 2008; Drury et al., 2009; Strock et al., 2011; King et al., 2015; Chatterjee, 2016).

Drainage effect on crop yield and residual soil NO_3-N

Studies conducted under wide variation of soil have indicated substantial crop yield improvements in soils with subsurface drainage that were not conventionally tile drained (Nelson et al., 2011). In the research conducted in the Edina soil series, Schwab et al. (1957) found 0.21 to 0.57 Mg ha^{-1} acre higher corn and oat yield at 4.57 and 9.14 m tile spacing compared to 18.29 m spacing. In their other study in silty loam soil Schwab et al. (1966) found significantly higher corn yield for drained treatment then undrained. Cotton, clover, rice, and wheat yield significantly increased by subsurface tile drains installation in long-term field drainage experiment in Middle Nile delta (Moustafa et al., 1987). Six-year study in central Indiana in Drummer silty clay soil showed subsurface tile drain maximized both crop productivity and nitrogen accumulation in grain (Hofmann et al., 2004). Doty et al. (1975) in research conducted in Southern Coastal Plains, which contain millions of acres of sandy soils, suggested use subsurface drainage to avoid excess water in soil profile and ponding during the periods of heavy or extended rainfall.

Subsurface drainage increases the discharge of nitrate nitrogen (NO_3-N) and decreases the loss of organic N in drainage water and loss of NO_3-N from system is greatly influenced by the amount of N applied to crop (Gilliam et al., 1999). Controlled drainage and shallow drainage reduced overall drainage volume by 37 % and 46 % respectively whereas annual NO_3-N loss for the study period was reduced by 36 % and 29 % for controlled and shallow drainage respectively. However, there was no statistical difference in soybean yield and undrained plots have slightly less corn yield (Helmers et al., 2012).

Tillage and crop rotation effect on crop yield and residual soil NO_3-N

In the study conducted under Fillmore silty clay loam soil in Nebraska, reduction in yield was observed with continuous use of no-till planting which might be due to soil compaction and poor soil aeration. Research also show significant yield increase with the periodic use of the moldboard plow as compared to continuous no-till (Dickey et al., 1983). Griffith et al. (1988) concluded that no-till yields are not likely to be competitive for long-term continuous corn on dark soils whereas, corn when rotated with soybean yields similar with conventional tillage and ridge-planted but 3% yield decrease was observed with no-till in their long-term study conducted in Central Corn Belt. Higher grain yield and dry matter was reported under corn grown in rotation with soybean, oat and clover. The requirement for nitrogen fertilizer for was less for rotated corn than continuous corn for maximum yield (Peterson and Varvel, 1989). Brown et al. (1989) found corn yields for no-till were lower than reduced tillage and there was no difference in soybean yields due to different tillage practices in eight year study in southeast Iowa from 1980-1987.

No-till system recorded significant less yield than all other tillage systems (conventional, sweep plow, subsoil-ridge, disk) for corn and soybean in somewhat poorly drained soil in east central Illinois (Mclsaac et al., 1990). Long-term study conducted in Ohio showed that no-till is benefited for corn and soybean yield in well-drained soil as the years progress whereas negative impacts of NT on poorly drained soil can be overcome by rotation, disease resistant varieties (Dick et al., 1991). Kladivko et al. (1991) found greatest loss of NO_3-N on area basis from 5-m tile spacing whereas, least was from 20-m tile spacing. The NO_3-N loss ranged from 18 kg ha^{-1} on 20-m tile spacing to 70 kg ha^{-1} on 5-m spacing during study period (1986-88) in Clermont soil of Indiana. Vepraskas et al. (1992) reported no difference in corn yield among three different tillage system (slit-till, subsoiled and no-till) on Norfolk loamy sand in Florence, South Carolina.

Conventional tillage recorded greatest tile drainage when compared with ridge and no-tillage. Surface runoff showed lower nitrate losses when compared to tile drainage with maximum of 2.6 kg ha^{-1} for ridge tillage and no-tillage treatment, but both treatments (ridge and no-till) had greater yields and N uptake in grain than conventional tillage system (Drury et al., 1993). Lund et al. (1993) found reduction of corn yield (10 %) and soybean (15 %) for continuous cropping compared with rotations and greatly reduction under no-till that moldboard plough during three-year study in Arlington, Wisconsin.

Levanon et al. (1993) observed significant NO_3-N leaching under plow tillage than no-till and suggested this might be due to greater mineralizing activity of the plow tillage. The loss of N in dry years were equivalent to less than 3 % of the N fertilizer applied whereas, it rise from 25 to 70 % during wet years. About 20 % of recommended fertilizer N applied was lost in the form of NO_3 losses through tile drainage during 11 years study in Ohio. The difference in corn yield and N uptake between convention tillage and no-till began to widen in four years and this difference was due to NO_3 losses in the drainage (Randall and Iragavarapu, 1995). West et al. (1996) found higher corn and soybean yields in rotation than in continuous cropping for all tillage system and response was more positive with no-till. Chisel and ridge plow had recorded 3 % less yield compare to plowing in all rotation (continuous corn, continuous soybean and corn soybean rotation).

Randall et al. (1996) suggest the use of moldboard plough over chisel or disc chisel but MB plow leaves inadequate residue for erosion protection and suggest for vegetative filter strips along rivers, streams, drainage ditches that may be required to reduce sediment losses. Study conducted on Floyd loam in Iowa showed that continuous corn in no-till plots had higher average drainage than moldboard plow and subsurface drainage under corn soybean rotation is lower that under continuous corn for all tillage except ridge tillage. Ridge and no-till system preserve macropores network better than chisel or moldboard plough which cause differ in tile drainage volume (Kanwar et al., 1997).

Porter et al. (1997) reported corn yield increased by 13 % when rotated with soybean and soybean annually rotated with corn yields 10 % more yield than continuous soybean in study conducted in Minnesota. Vetsch and Randall (2002) found tillage has no significant effect on corn yield in corn soybean rotation when averaged across year's difference in corn yield.

In the study conducted in Ontario, no-tillage was found to have higher tile drainage volume and NO_3 loss might be due to increase in soil macropores contributed by earthworm population. Nitrate loss through drainage water reduced by 14 % in conventional tillage and 26 % in no-tillage under controlled drainage system when compared with free drainage system. Conventional tillage site recorded 12 to 14 % greater soybean yield compared to no-till site (Tan et al., 1998)

Dinnes et al. (2002) suggested improved timing and rate of N fertilizer application using soil test and plant monitoring, diversifying crop rotations using cover cropping, reduced tillage and using nitrification inhibitors for increasing corn yield. Corn rotated with soybean produced 17 % higher corn yield than continuous corn and soybean yield was 12 % higher when rotated with corn than continuous soybean (Pedersen and Lauer, 2003). Katsvairo and Cox (2000) reported similar corn yield under chisel and moldboard plow whereas, 10 % less yield was observed with low vs high chemical management in dry years and 25 % yield loss in wet years. Similarly, under ridge tillage, 25 % less corn yield was noted with low vs. high chemical management irrespective of dry and wet years. Corn grain yield was affected by tillage and rotation practices whereas, soybean was only affected by rotation not tillage on study conducted on silty clay loam soil in Nebraska. Soybean (2.57 Mg ha^{-1}) and corn (7.10 Mg ha^{-1}) yield was higher for rotation when compared with continuous cropping (2.35 and 5.83 Mg ha^{-1}) respectively. The benefit of rotation for corn yield depend upon temperature during spring (cool spring was beneficial) whereas, soybean yield did not vary with weather conditions. The effects of tillage and rotation on corn yield was influenced by seasonal temperature and rainfall patters (Wilhelm and Wortmann, 2004).

Higher soluble nutrient losses in surface runoff and subsurface drainage (due to macropores flow) occurs with tillage system that do not incorporate surface residue whereas, tillage system that thoroughly mix residue and amendments in surface soil appears to be more prone to sediment and sediment-associated nutrient losses (particulate P) via surface runoff (Zhao et al., 2001). Direct drilling (no-till) improve soil aggregation, avoids soil degradation and improve soil organic matter but conventional tillage (moldboard with chisel plow) provides better yield compared to no-till in clay loam soil in Central Iran (Hajabbasi and Hemmat, 2000).

Subsurface drain spacing and depth effect on crop yield and residual soil NO_3-N

Tile drainage study conducted by Hoover and Schwab (1969) in north central Ohio indicated that narrow (30-ft) drain spacing resulted in higher drain discharge that the wider (60-ft) spacing. This shows that narrow drain spacing removes soil water faster and reduce moisture content of soil to field capacity earlier in the growing season. They also mentioned that long season crops resulted in lower tile drainage that crops that grows actively in show growing season when compared between oat and meadow crop. Wright and Sands (2001) mentioned close relationship between soil permeability, crop grown, desired drainage coefficient, degree of surface drainage and recommended tile spacing and depth.

In three out of 10 years of study in Indiana, 5-m drain spacing recorded 1.3 to 1.7 Mg ha^{-1} higher corn grain yield than non-drained control and was likely due to delay in planting date and wetter soil condition after planting. Remaining seven out of 10 years observed less than expected yield difference that might be due to excellent surface drainage or optimal planting date. This shows that tile drainage is not supposed to benefit farmers with high yield every years (Kladivko et al., 2005). The Agricultural Drainage and Pesticide Transport simulation model indicate that greater reductions in NO_3-N losses occur with reduced N application rates than with increases in drain spacing or decrease in drain depth (Davis et al., 2000). Cooke et al. (2002) reported direct correlation between decreased tile flow and decreased tile depths and same patterns holds true for NO_3 mass loads. Simulation study conducted in North Carolina showed that N losses from subsurface drains can be reduced by placing the drains at shallow depth (Skaggs and Chescheir, 2003). Strock et al. (2011) mentioned increase in cost of system with reduction of drain spacing and depth. Sands et al. (2008) stated timing and amount of annual rainfall variability, dry-wet precipitation sequences and cropping sequences as primary factor for variability in annual subsurface drainage volume and NO_3 loads. They also found significant effect of shallower and less intense drainage system in 20 % reduction of drainage volume and 18 % reduction of nitrate loading.

In the study conducted in southern Indiana, narrower drain spacing had greater drain flow and NO_3 losses per unit areas and drain flow remove 8-26 % of annual rainfall depending upon year. There was no difference in nitrate N concentration in drain flow with spacing but concentration have significantly decreased from beginning to end of experiment (Kladivko et al., 2004). Simulation study conducted by Nangia et al. (2010) shows results on reduction of NO_3-N losses by decreasing depth and increasing spacing of tile drains. Reduction of 31 % of NO_3-N was observed when drain depth was reduced from 1.5 to 0.9 m but also reduction of crop yield by 60 % was observed whereas, increasing tile drain spacing from 27 to 40 reduced NO_3-N by 50% with only 7 % of yield reduction. Hofmann et al. (2004) noted maximum crop productivity and nitrogen accumulation in grain under lateral spacing of tile drains of 20 m but increased nitrate loading of surface water when compared to a less dense spacing in six years study conducted in central Indiana.

Previous research studies on tile drainage, crop rotation and tillage systems were studied separately or only two factors are considered for study in well drained to poorly drained soils for yield. Information on the long-term impact of different types of tile drainage, rotation and tillage system on corn, soybean yield and residual soil nitrate in poorly drained clay soil is needed. Deciding on subsurface drain depth and spacing also influences nutrient loss, closer drain spacing results in fast removal of excess water but also involves increased cost of installation. Wider drain spacing could reduce the cost but also significantly could reduce the yield due to prolonged water stress condition. Installation of control structures in subsurface drainage system provide an opportunity to control.

Therefore, the objectives of this study were to (i) study interactive effect of drainage, rotation and tillage on corn and soybean yield; (ii) determine the residual soil nitrate due to combine effect of drainage, rotation and tillage; (iii) determine the effect of different subsurface drain spacing and depth combinations on crop yield and (iv) estimate the nutrient availability as influenced by different subsurface drain spacing and depth combination.

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CHAPTER 1. EFFECT OF TILE DRAINAGE, CROP ROTATION AND TILLAGE ON CROP YIELD IN FARGO CLAY SOIL

Abstract

Subsurface drainage has recently become common for agriculturally productive clay soils in the Northern Great Plains of USA. However, evidence-based recommendations regarding best combinations of drainage, tillage and crop rotation are lacking on these frigid clay soils. Therefore, a four-year (2014-17) study was conducted near Casselton, ND to evaluate the effects of subsurface drainage [conventional drainage (OT), controlled drainage (CD) and no drainage (check - no drainage only)], crop rotation [continuous corn (CC), corn-soybean (CS)] and tillage [chisel plow (CH), no till (NT) and strip till (ST)] on corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] yields. Drainage, crop rotation, tillage and their interactions significantly affected corn yields during 2014-2017. Corn yield was similar between drainage except for 2014 and 2015 when 22% and 8% greater yield occurred with no drainage respectively. Corn in rotation (CS) produced 28, 53 and 8% significantly higher yield than CC in 2015, 2016 and 2017 respectively. Chisel plow recorded 12, 9, 8% significantly higher corn yield in 2014, 2016 and 2017; whereas, strip till observed 5% significantly higher in 2015 than NT. Four-year average showed significant highest corn yield (10.98 Mg ha^{-1}) under no drainage, CS and CH combination. Soybean yield was not affected by drainage and tillage except for drought year of 2017 when 18% greater yield occurred with chisel plow and no drainage with chisel plow combination recorded highest soybean yield (4.48 Mg ha^{-1}). Plant available water is typically assumed to exclude water held between saturation and field capacity. However, this assumption is not valid in poorly drained, slow permeable clay soils where soil water held between saturation and field capacity do not rapidly contribute to deep percolation, and is therefore available to the

plant. By installing subsurface drains and allowing a pathway for rapid drainage, this fraction of soil water is now allowed to rapidly drain and consequently become unavailable to plants. In years with drought conditions after snowmelt, this could potentially lead to less total water available for the plants during the growing season.

Key words: controlled subsurface drainage, corn-soybean rotation, no-till

Introduction

Subsurface drainage is a common, but expensive, agriculture practice (Palvelis, 1987) to remove standing or excess water in agricultural fields. However, these drainage practices help facilitate timely cultural practices and planting of crops in the Northern Great Plains region (Zucker and Brown, 1998). The number of United States (US) farms with subsurface drainage systems in 2012 was > 217,000 (i.e., 14% of total) covering 48.6 million acres (12.5% of total) cropland (USDA, 2012). Subsurface drainage systems are designed to maintain soil conditions near field capacity after heavy rainfall. Therefore, these systems aid with decreasing surface runoff, increasing soil aeration and trafficability, promoting quick germination of seeds and subsequently deeper root growth, extending the growing season in frigid clay soils, and ultimately improving crop yields (Sands, 2001; Strock et al., 2011; King et al., 2015). Some research studies have shown higher corn yield under subsurface drainage (Schwab et al., 1957, 1966; Moustafa et al., 1987; Hofmann et al., 2004), whereas others (Awale et al., 2015) found no effects on corn yields. However, subsurface drainage can potentially increase organic matter mineralization and nitrification, decrease denitrification, and create a direct pathway for soluble nitrogen movement to surface waters (Randall and Goss, 2008; Dinnes et al., 2002). Therefore, subsurface drainage can potentially enhance crop production on poorly drained clay soils, but can also increase the risk of nitrogen losses through leaching (Dinnes et al., 2002; David et al., 2010; Woli et al., 2010). Controlled drainage is a common option for reducing drainage rates when maximum drainage is not required (Skaggs and Schilfgaarde, 1999) and can reduce leaching losses of nutrients, such as NO_3-N (nitrate-nitrogen), via drainage waters (Gilliam et al., 1999; Drury et al., 2014; Schott et al., 2017).

Subsurface drainage may promote the adoption of conservation tillage practices. Many US farmers have adopted some form of reduced tillage [strip till [ST] and no-till (NT)] from conventional tillage [chisel plow (CH) and moldboard plow] (Logan et al., 1987). However, mixed results have been reported on crop yield effect of chisel plow vs no-till. Response to rotation was consistent after first four years of study where CH yielded 11% and no till planting had 20% higher corn yield in corn-soybean (CS) than continuous corn (CC) rotation (Griffith et al., 1988) in central Indiana. In contrast, NT fields had significantly higher corn yield than chisel plow and moldboard plow for 13 years in CC and CS rotation and 11 years for soybean yield in CS rotation during a 28 years long study in Nebraska (Sindelar et al., 2015). However, little to no difference in yield was observed between NT and CP for long-term corn and soybean plots across the Midwestern US region (Daigh et al., 2018). Conservation tillage practices have been widely used in row crops as corn and soybean, since it minimizes erosion and surface runoff thereby improving water infiltration (Reganold et al., 1990). Randall and Iragavarapu (1995) reported that high drain flow under NT does not necessarily result in higher nitrate leaching. In dry years, with less moisture in soil, conservation tillage helps in N mineralization when plant growth and N uptake are limited and percolation of soil water is negligible (Randall and Iragavarapu, 1995). Tonitto et al. (2007) reported NO_3-N leaching could be reduced by 30-50% under corn and by 15-50% under soybean crops using diversified rotations (corn-soybean-wheat and corn-rye-soybean-rye) relative to conventional CS rotation. Probability of increases in corn yield was higher with no-till when grown in rotation on well-drained soil in southern latitude of US (Griffith and Wollenhaupt, 1994).

Previous research studies most often evaluated crop yield response to subsurface drainage, crop rotation or tillage systems separately or, at most, in combination of just two factors. Knowledge of the crop yield impacts and nitrogen fate within subsurface drainage, crop rotation and tillage system combinations are therefore rare. Moreover, the effects on corn and soybean yields and residual soil nitrate in poorly drained; fridged clay soils of the north is needed to make evidence-based recommendations to agricultural producers. Therefore, the objectives of this study were to (i) evaluate the effects of drainage, crop rotation and tillage on corn and soybean yields in a Fargo clay soil in North Dakota, and (ii) determined residual soil nitrate levels of these systems at the end of the growing season.

Material and methods

Site description and experimental design

A field experiment was conducted for four growing seasons (2014-2017) near Casselton, North Dakota (46°49'25.03"N, 97°13'5.70"W) on a poorly drained Fargo silty clay soil (fine, smectitic, frigid typic epiaquerts) (Soil Survey Staff, 2013). The field was in a long-term corn/wheat/soybean crop rotation with CH tillage prior to establishment of the experimental plots in 2013. Subsurface drains were installed at 9.14 m spacing and 0.91 m depth in 2013 and experimental plots were laid out in same year. The 30-year average precipitation is 598 mm per annum and air temperature is 5.33°C. The 30 year average air temperature ranges from 13.4 to 21.3 °C (NDAWN, 2017). There are 138 frost-free days from May 11 to September 27. The slope of field site ranges from 0-1 percentage. Soil was collected at start of experiment in 2013 and basic chemical properties analyzed (Table 1.1).

Table 1.1. Basic chemical properties of experimental site used to determine the effect of drainage, rotation and tillage on corn and soybean during 2014-2017 growing seasons, located at Casselton, ND

Chemical properties	
pH	6.4
EC (ds m^{-1})	0.7
NO_3-N (kg ha^{-1}) - 60 cm	21.3
Olsen-P (mg kg^{-1})	48
K (mg kg^{-1})	470
Ca (mg kg^{-1})	4720
Mg (mg kg^{-1})	900
Na (mg kg^{-1})	14

Soil pH and electrical conductivity (EC) were measured using pH/CON 450 meter (Oakton Instruments, Vernon Hills, IL, USA) with soil water ratio of 1:2.5 (Thomas, 1996). Inorganic nitrogen ($NH4^{+}$+$NO3^{-}$) concentration was determined by extracting 5 g soil samples with 2M KCl and subsequently analyzed the aliquot with TL-2800 ammonia analyzer (Timberline Instruments, Boulder, CO, USA) using KCl extraction (Maynard et al. 2008). The concentration of soil available phosphorus (P) or Olsen-P, was measured spectrophotometrically after extraction of soils with sodium bicarbonate (Olsen et al., 1954). Exchangeable cations (Ca, Ma , K and Na) were determined using Atomic Absorption Spectroscopy (Thomas, 1982).

The field experiment was a strip-split-plot randomized complete block design with four replicates. Three drainage system *viz.* (i) conventional drainage (OT) (ii) controlled drainage (CD) and (iii) no drainage (check-surface drainage only) were placed in three strips as main plot. Controlled structure was set at 0.3 m below soil surface during all growing season in dry period and 0.9 m below soil surface at wet period. Over each strip, two cropping systems, continuous corn (CC) and corn soybean (CS), were randomized as sub-plot, and then under each sub-plot three tillage practices, (i) chisel plow (CH), (ii) strip-till (ST) and (ii) no-till (NT) were randomized as sub-sub plot. Individual treatment dimension was 9.1 by 3.4 m.

Urea was applied as source of nitrogen at 179.3 kg N ha^{-1} in the last week of September after harvest. No N was applied for soybean crop. After harvest in the fall, CH plots were tilled using Kongskilde Triple K field cultivator that has S-tine shank and double spiral roller behind at depth of 7.5 cm. Field cultivator was used to smooth the soil surface prior to planting in spring. Wil-rich Strip Tiller was used for strip tillage at 25 cm depth in strip-till plot only in fall and no till plots were undisturbed. Roundup Ready Soybean (Mustang 0443) and corn (Dekalb C39-27Ri13) cultivars were planted at 415,000 and 84,000 plants ha^{-1} respectively, using 55.9 cm wide seed drill every year in the first week of May. The mixture of Roundup (Isopropylamine salt of glyphosate a.i.) 25 ml $liter^{-1}$ and Class act (water conditioning agent) 10 ml $liter^{1}$ was sprayed twice (last week of May and third week of June) to control weeds. At physiological maturity, the middle three rows of each plot were harvested using the small plot combine harvester on the last week of September for soybean and third week of October for corn every year. The grain yield (Mg ha^{-1}) for soybean and corn was calculated using 14% moisture content.

Measurement of inorganic nitrogen content

Soil cores (2 cm diam.) were collected to a depth of 0-15 cm and 15-60 cm from each plot at harvest to determine the soil inorganic N level. Two soil cores from each plot were composited, transferred to laboratory at 5°C, and stored at -18°C until analysis within a week. After thawing and homogenizing frozen soil, 6.5 g of moist soil was extracted with 25 mL of 2 M KCl (1:5 soil/extractant ratio) after shaking for 30 min (Maynard et al., 2008). The KCl extracts were analyzed using Timberline TL2800 Ammonia Analyzer (Timberline Instruments, CO, USA). Soil moisture content and bulk density were determined by gravimetric method at 105°C using separately weighed subsamples of soil for both depths using 2 cm diameter hand probe. Bulk density of respective soil depth was multiplied with inorganic nitrogen concentration to express them weight on area basis, densities of two depths were multiplied with respective NH_4^+ and NO_3^- (mg kg^{-1}) to express them into area basis (kg ha^{-1}). Finally, total inorganic N for both depths (0-15 and 15-60 cm) were summed to obtain total inorganic N content for 0-60 cm depth.

Statistical analysis

Crop yields and residual soil NO_3-N for corn plots were subjected to general linear model analysis of variance PROC GLM. Fixed effects include drainage, rotation and tillage system; whereas, replication, replication × rotation and replication × rotation × drainage were random effects for corn yield analysis. Corn yields for each year were analyzed separately as well as their four-year means. . Soybean yields and residual soil NO_3-N were similarly analyzed using PROC GLM. Drainage and tillage were fixed effects; whereas, replication and replication × drainage were random effects. Soybean yields for each year were analyzed separately as well as their four-year means. Fisher's protected least square difference (LSD) at $\alpha = 0.05$ was used to separate treatment means. All statistics were analyzed using Statistical Analysis System software (SAS, 2013)

Results

Climatic conditions

Monthly mean air temperature and cumulative rainfall during the growing season of 2014-2017 are presented in Table 1.2. Average air temperature was near the 30-year average for the study period. Total rainfall for 2014-2017 was 17, 16, 22, and 46% less than 30-year average (397 mm), respectively. Rainfall in May and July, 2014, were 33 and 74% less than the 30-year average; whereas, June and August was 10 and 22% above the 30-year average. During 2015, rainfall in July, August, and September was 58, 36 and 78% lower and May was 73% higher as compared to the 30-year average, respectively. Rainfall in May, June, and August,2016, was 39, 53 and 16% less, respectively, than the 30-year average; whereas, May, June, July and August, 2017, were the driest months with 71, 61, 58 and 25 less than the 30-year average, respectively.

Table 1.2. Monthly mean air temperature (°C) and monthly total precipitation (mm) for 2014-17 and the 30-year long-term average at research site, Casselton, North Dakota.

Month	Average air temperature (°C)					Precipitation (mm)				
	2014	2015	2016	2017	30 year average	2014	2015	2016	2017	30 year average
May	13	12	15	13	13	52	134	47	22	76
June	19	19	20	19	19	111	108	47	39	100
July	20	22	21	21	21	23	37	89	37	88
August	20	20	20	18	20	81	42	56	50	67
September	15	18	16	16	15	65	14	72	69	66
Mean/total	17	18	18	17	18	332	335	311	217	397

Source: NDAWN. North Dakota Agricultural Weather Network. 2017. North Dakota State University, Fargo, ND. Available at http://ndawn.ndsu.nodak.edu (verified November 10, 2017) and 30-year average (1981-2010)

Main effects on corn yield

Drainage, crop rotation and tillage effects on corn yield from 2014-2017 and 4-year average are presented in Table 1.3. In 2014, drainage (*P=0.003*), rotation (*P=0.001*) and tillage (*P=0.001*) had significant effect on corn yield. Among the drainage treatments, no drainage recorded highest corn yield (7.86 Mg ha^{-1}), and the lowest yield was found under controlled drainage (6.43 Mg ha^{-1}). Among the crop rotations, CC yielded 37% higher than CS rotation (6.14 Mg ha^{-1}). Among three tillage treatments, CH had the highest corn yield (7.63 Mg ha^{-1}), and the lowest yield was found with NT (Mg ha^{-1}). Similarly in 2015, corn yield was significant for drainage (*P=0.008*), rotation (*P=0.001*) and tillage (*P=0.017*). Among drainage, highest corn yield (7.66 Mg ha^{-1}) was observed with no drainage, and the lowest was found under conventional drainage (7.09 Mg ha^{-1}). CS rotation recorded 20% higher corn yield (8.24 Mg ha^{-1})

compared to CC rotation. Corn yield under strip-till (7.51 Mg ha^{-1}) was highest and NT had the lowest yield (7.16 Mg ha^{-1}).

Table 1.3. Corn yields (Mg ha^{-1}) under drainage (CHECK, OT and CD), rotation (CS and CC) and tillage (CH, NT and ST) during the 2014-17 growing seasons and 4-year average.

	2014	2015	2016	2017	4-year average
Drainage	-----------------------------------Mean yield (Mg ha^{-1})--------------------------------				
Check	7.86 a¶	7.66 a	10.66	13.44	9.90 a
OT	7.56 a	7.23 b	10.52	12.70	9.41 b
CD	6.43 b	7.09 b	10.50	12.47	9.22 c
P>F	*0.003*	*0.008*	*0.258*	*0.159*	*0.001*
Rotation					
CC	8.43 a	6.41 b	08.32 b	12.27 b	8.86 b
CS	6.14 b	8.24 a	12.80 a	13.47 a	10.16 a
P>F	*0.001*	*0.001*	*0.001*	*0.001*	*0.001*
Tillage					
CH	7.63 a	7.31 ab	11.08 a	13.29 a	9.83 a
ST	7.40 a	7.51 a	10.21 b	12.29 b	9.36 b
NT	6.82 b	7.16 b	10.39 b	13.03 a	9.35 b
P>F	*0.001*	*0.017*	*0.001*	*0.002*	*0.001*

¶ Values within a column for a period followed by same letter are not significantly different at P<0.05 according to LSD test

Except drainage (P=0.159) crop rotation (P=0.001) and tillage (P=0.001) had significant effect on corn yield in 2016. CS rotation (12.80 Mg ha^{-1}) had 55% higher corn yield compared to CC rotation. Among tillage, CH recorded the highest corn yield (11.08 Mg ha^{-1}) and the lowest was found with ST (10.21 Mg ha^{-1}). In 2017, corn yield was significant for rotation (*P=0.001*) and tillage (*P=0.002*) whereas, drainage (*P=0.159*) had no significant effect. Corn-soybean rotation recorded highest corn yield compared to CC (12.27 Mg ha^{-1}). Chisel plow recorded highest corn yield (9.83 Mg ha^{-1}) and the lowest was found with ST (12.29 Mg ha^{-1}).

When averaged over four years, corn yield was significantly affected by drainage (*P=0.001*), rotation (*P=0.001*) and tillage (*P=0.001*). Highest corn yield was observed with no drainage (9.91 Mg ha^{-1}) and, the lowest by controlled drainage (9.22 Mg ha^{-1}) whereas, CS rotation observed yield of 10.2 Mg ha^{-1} compared to CC (8.86 Mg ha^{-1}). Chisel plow recorded highest yield of 9.83 Mg ha^{-1} and the lowest yield was observed with NT (9.35 Mg ha^{-1}).

Two-way interaction effects on corn yield

The two-way interaction among drainage, rotation and tillage for corn yield from 2014-2017 and 4-year average are presented in Table 1.4. In 2014 growing season, drainage × rotation (P=0.011), rotation × tillage (P=0.001) and drainage × tillage (P=0.001) interaction had significant effect on corn yield. Interaction between drainage and rotation showed no drainage with CC (9.04 Mg ha^{-1}) recorded highest corn yield and, the lowest observed under controlled drainage with CS interaction (4.95 Mg ha^{-1}). Highest corn yield (9.21 Mg ha^{-1}) was observed with CC under CH and the lowest yield was observed with CS×NT (6.05 Mg ha^{-1}). Combination of no drainage with CH (8.68 Mg ha^{-1}) had the highest corn yield; whereas, controlled drainage with NT recorded the lowest yield (5.80 Mg ha^{-1}). Similarly, interaction among drainage, rotation and tillage effect on corn yield was significant during 2015 growing. For drainage × rotation, no drainage with CS (8.69 Mg ha^{-1}) recorded the highest corn yield, and the lowest yield was observed under controlled drainage with CC (6.01 Mg ha^{-1}). Highest corn yield of 8.85 Mg ha^{-1} was observed under CS × ST, it was 43% higher than lowest recorded yield under CC×ST. Likewise, highest corn yield was observed with no drainage under NT (8.16 Mg ha^{-1}) whereas, the lowest yield was found with conventional drainage under NT (6.35 Mg ha^{-1}).

Table 1.4. Corn yields (Mg ha^{-1}) at different two-way interaction among drainage (CHECK, OT and CD), rotation (CS and CC) and tillage (CH, NT and ST) during the 2014-17 growing seasons and 4-year average

	2014	2015	2016	2017	4-year average
Drainage × Rotation	----------------------------	Mean yield (Mg ha^{-1})	----------------------------		
CD × CC	7.90 b¶	6.01 d	8.08 c	12.14 b	8.53
CD × CS	4.95 d	8.45 a	12.95 a	13.26 a	9.90
OT × CC	8.34 b	6.60 c	8.37 bc	11.36 c	8.67
OT × CS	6.78 c	7.59 b	12.63 a	13.59 a	10.15
Check × CC	9.04 a	6.63 c	8.50 b	13.31 a	9.37
Check × CS	6.69 c	8.69 a	12.82 a	13.57 a	10.44
P<F	*0.011*	*0.006*	*0.048*	*0.003*	*0.080*
Rotation × Tillage					
CC × CH	9.21 a	6.58 c	9.02 c	12.29 c	9.28 c
CC × NT	7.89 b	6.48 cd	7.95 d	12.56 c	8.72 d
CC × ST	8.19 b	6.18 d	7.98 d	11.96 c	8.58 d
CS × CH	6.05 d	8.04 b	13.13 a	14.30 a	10.38 a
CS × NT	5.75 d	7.84 b	12.83 a	13.50 b	9.98 b
CS × ST	6.62 c	8.85 a	12.44 b	12.63 c	10.13 b
P<F	*0.001*	*0.001*	*0.021*	*0.032*	*0.022*
Drainage × Tillage					
CD × CH	6.10 e	7.78 a	11.40 a	13.19 bc	9.62 b
CD × NT	5.80 e	6.97 b	10.06 a	12.41 cd	8.81 e
CD × ST	7.38 cd	6.95 b	10.09 b	12.50 cd	9.23 cd
OT × CH	8.12 ab	7.13 b	10.67 b	12.57 cd	9.62 b
OT × NT	6.86 d	6.35 c	10.68 bc	12.59 cd	9.12 d
OT × ST	7.71 bc	7.81 a	10.15 bc	12.26 d	9.48 bc
Check × CH	8.68 a	7.02 b	11.16 c	14.12 a	10.25 a
Check × NT	7.79 bc	8.16 a	10.42 c	14.08 ab	10.11 a
Check × ST	7.12 d	7.79 a	10.40 c	12.12 d	9.36 bcd
P<F	*0.001*	*0.001*	*0.005*	*0.003*	*0.001*

¶ Values within a column for a period followed by same letter are not significantly different at P<0.05 according to LSD test

During 2016, drainage × rotation (*P=0.048*), rotation × tillage (*P=0.021*) and drainage × tillage (*P=0.005*) interaction had significant effect on corn yield. Corn yield was highest with controlled drainage under CS rotation (12.95 Mg ha^{-1}) and the lowest yield was observed with controlled drainage under CC rotation (8.08 Mg ha^{-1}). In rotation × tillage, CS with chisel plow

(13.13 Mg ha^{-1}) recorded the highest corn yield; whereas, the lowest was found with CC×NT (7.95 Mg ha^{-1}).Controlled drainage under CH (11.40 Mg ha^{-1}) recorded highest corn yield and, the lowest was found with controlled drainage under NT (10.06 Mg ha^{-1}). Likewise, in 2017, two-way interaction among drainage, rotation and tillage had significant effect on corn yield. Highest corn yield was observed with conventional drainage under CS (13.59 Mg ha^{-1}) and, the lowest was found with conventional drainage under CC rotation (11.36 Mg ha^{-1}). The highest corn yield was recorded with CS×CH (14.30 Mg ha^{-1}) and, the lowest was found with CC×ST (11.96 Mg ha^{-1}). No drainage with CH recorded highest corn yield of 14.12 Mg ha^{-1}, which was 17% higher than lowest yield recorded by no drainage with ST.

When averaged over four years, only rotation × tillage (P=0.022) and drainage × tillage (P=0.001) had significant effect on corn yield. In drainage × tillage, no drainage under CH recorded highest corn yield of 10.2 Mg ha^{-1}; whereas, the lowest was observed with controlled drainage under NT (8.81 Mg ha^{-1}). Highest corn yield was observed with CS×CH (10.4 Mg ha^{-1}) and, the lowest was observed with CC×ST (8.58 Mg ha^{-1}).

Three-way interaction effect on corn yield

Three-way interaction among drainage, rotation and tillage for corn yield from 2014-2017 and 4-year average are presented in Table 1.5. Drainage × rotation × tillage had significant effect on corn yield in 2014 ($P=0.017$), 2015 ($P=0.001$), 2016 ($P=0.06$) and 4-year average ($P=0.004$), whereas, no interaction effect was observed in 2017 ($P=0.461$). During 2014 growing season, highest corn yield (9.92 Mg ha^{-1}) was recorded in no drainage with CC rotation under chisel plow and, controlled drainage with CS rotation and CH tillage had lowest yield (4.05 Mg ha^{-1}). Similarly, in 2015, corn yield was highest (9.45 Mg ha^{-1}) for conventional drainage with CS rotation under strip tillage that was 68% higher than the lowest observed for controlled drainage with CC rotation under NT.

Table 1.5. Corn yields (Mg ha^{-1}) at three-way interaction among drainage (CHECK, OT and CD), rotation (CS and CC) and tillage (CH, NT and ST) during the 2014-17 growing seasons and 4-year average

Drainage × Rotation × Tillage	2014	2015	2016	2017	4-year average
	-----------------------Mean yield (Mg ha^{-1})---------------------------				
CD × CC ×CH	8.15 cdef¶	6.66 de	9.17 d	12.45	9.11 f
CD × CC × NT	7.38 fg	5.64 g	7.69 gh	11.79	8.13 g
CD × CC × ST	8.18 cde	5.73 g	7.38 h	12.17	8.36 g
CD × CS × CH	4.05 j	8.89 a	13.62 a	13.93	10.12 c
CD × CS × NT	4.22 j	8.30 b	12.43 bc	13.03	9.50 de
CD × CS × ST	6.57 hi	8.17 b	12.80 b	12.82	10.09 c
OT × CC × CH	9.55 ab	6.99 cd	9.06 d	11.21	9.21 ef
OT × CC × NT	7.45 efg	6.64 def	7.88 fgh	11.57	8.38 g
OT × CC × ST	8.02 def	6.16 efg	8.16 fg	11.29	8.41 g
OT × CS × CH	6.69 gh	7.26 c	12.28 bc	13.92	10.04 c
OT × CS × NT	6.26 hi	6.05 g	13.47 a	13.61	9.85 cd
OT × CS × ST	7.40 efg	9.45 a	12.13 c	13.23	10.55 b
Check × CC × CH	9.92 a	6.08 fg	8.82 de	13.21	9.51 de
Check × CC × NT	8.83 bc	7.14 cd	8.2 efg	14.30	9.63 d
Check × CC × ST	8.37 cd	6.66 def	8.4 ef	12.42	8.96 f
Check × CS × CH	7.43 efg	7.96 b	13.49 a	15.03	10.98 a
Check × CS × NT	6.76 gh	9.18 a	12.58 bc	13.86	10.59 b
Check × CS × ST	5.87 i	8.92 a	12.39 bc	11.83	9.75 cd
P<F	*0.0174*	*0.001*	*0.006*	*0.4605*	*0.004*

¶ Values within a column for a period followed by same letter are not significantly different at P<0.05 according to LSD test

Highest corn yield (13.62 Mg ha^{-1}) was recorded under combination of controlled drainage with CS rotation under chisel plow and lowest (7.38 Mg ha^{-1}) for controlled drainage with CC rotation under ST in 2016 growing season. When averaged across 4-years, no drainage with CS rotation under CH recorded highest corn yield (11.0 Mg ha^{-1}), whereas the lowest (8.13 Mg ha^{-1}) was found under controlled drainage with CC rotation and NT.

Main effects on soybean yield

Drainage and tillage effects on soybean yield from 2014-2017 and 4-year average are presented in Table 1.6. Drainage has no significant effect on soybean yield in all four growing season [2014, (*P=0.468*); 2015, (*P=0.115*); 2016, (*P=0.327*); 2017] and 4-year average (*P=0.268*). Whereas, tillage has significant effect on soybean yield only in 2017 (*P=0.001*) and 4-year average (*P=0.006*). During 2017 growing season, CH recorded the highest soybean yield (4.23 Mg ha^{-1}) and the lowest was observed with ST (3.84 Mg ha^{-1}). When averaged across 4-years, CH had the highest soybean yield (3.14 Mg ha^{-1}) whereas; ST (2.98 Mg ha^{-1}) recorded the lowest yield.

Table 1.6. Soybean yields (Mg ha^{-1}) under drainage (CHECK, OT and CD) and tillage (CH, NT and ST) during the 2014-17 growing seasons and 4-year average.

	2014	2015	2016	2017	4-year average
Drainage	---------------------------------Mean yield (Mg ha^{-1})---------------------------------------				
Check	2.22	2.19	3.68	4.17	3.07
OT	2.11	2.51	3.57	3.97	3.04
CD	2.11	2.39	3.70	3.94	3.03
P>F	*0.468*	*0.115*	*0.327*	*0.272*	*0.268*
Tillage					
CH	2.18	2.32	3.83	4.23 a¶	3.14 a
ST	2.11	2.44	3.53	3.84 c	2.98 b
NT	2.14	2.34	3.60	4.02 b	3.02 b
P>F	*0.478*	*0.335*	*0.081*	*0.001*	*0.006*

¶ Values within a column for a period followed by same letter are not significantly different at P<0.05 according to LSD test

Interaction effect on soybean yield

The two-way interaction among drainage and tillage for soybean yield from 2014-2017 and 4-years are presented in Table 1.7. Drainage × tillage interaction has significant effect on soybean yield only in 2017 (*P=0.003*). No drainage with CH recorded highest soybean yield (4.48 Mg ha^{-1}) whereas, lowest was observed with conventional drainage with NT (3.70 Mg ha-

$^{-1}$). There was no significant effect of drainage and tillage interaction in soybean yield; 2014, (*P=0.468*); 2015, (*P=0.579*); 2016 (*P=0.828*) and 4-year average, (*P=0.124*).

Table 1.7. Soybean yields (Mg ha^{-1}) at different two-way interaction among drainage (CHECK, OT and CD) and tillage (CH, NT and ST) during the 2014-17 growing seasons and 4-year average

	2014	**2015**	**2016**	**2017**	**4-year average**
Drainage × Tillage	-------------------------Mean yield (Mg ha^{-1})----------------------------				
CD × CH	2.19	2.31	3.87	3.86 cd¶	3.06
CD × NT	2.06	2.47	3.71	4.13 bc	3.09
CD × ST	2.07	2.39	3.51	3.83 d	2.95
OT × CH	2.09	2.44	3.82	4.34 ab	3.17
OT × NT	2.18	2.47	3.41	3.70 d	2.94
OT × ST	2.05	2.63	3.49	3.87 cd	3.01
Check × CH	2.26	2.21	3.79	4.48 a	3.18
Check × NT	2.18	2.08	3.67	4.22 ab	3.04
Check × ST	2.22	2.29	3.58	3.81 d	2.98
P>F	*0.4683*	*0.5798*	*0.8275*	*0.0031*	*0.124*

¶ Values within a column for a period followed by same letter are not significantly different at P<0.05 according to LSD test

Residual soil nitrate content

Soil NO_3-N content was significant for rotation (*P=0.02*) in 2016; whereas, soil NO_3-N in corn plots significantly responded to rotation (*P=0.001*) and tillage (*P=0.001*) (Table 1.8). In 2016, CC rotation (108.85 kg ha^{-1}) plots had highest residual NO_3-N compared to CS (86.68 kg ha^{-1}). Similarly in 2017 growing season, CS rotation plots recorded highest residual soil NO_3-N (68.49 kg ha^{-1}) and lowest with CC rotation (47.02 kg ha^{-1}). Residual soil NO_3-N was highest under CH (91.96 kg ha^{-1}) and lowest with ST (34.90 kg ha^{-1}).

Table 1.8. Residual soil NO_3-N under drainage (CHECK, OT and CD), rotation (CS and CC) and tillage (CH, NT and ST) during the 2016 and 2017 growing seasons in corn and soybean plots.

	Corn		Soybean	
	2016	**2017**	**2016**	**2017**
Drainage	------------Residual soil NO_3-N (kg ha $^{-1}$) ----------------			
Check	87.15	66.65	29.77	9.59 b¶
OT	96.78	53.02	23.74	20.45 a
CD	108.85	53.59	18.43	11.52 b
P>F	*0.698*	*0.080*	*0.115*	*0.043*
Rotation				
CC	108.51 a	47.02 b	--	--
CS	86.68 b	68.49 a	--	--
P>F	*0.018*	*0.001*	--	--
Tillage				
CH	96.10	91.96 a	24.23	13.06
ST	101.06	34.90 b	22.04	15.30
NT	95.62	46.40 b	25.66	13.20
P>F	*0.819*	*0.001*	*0.373*	*0.529*

¶ Values within a column for a period followed by same letter are not significantly different at $P<0.05$ according to LSD test

In 2017, rotation × tillage has significant influence on residual soil NO_3-N in three different drainage treatment in corn plots. CH under CS rotation recorded highest residual soil nitrate for controlled drainage (104.7 kg ha^{-1}), conventional drainage (124.6 kg ha^{-1}) and no drainage (153.79 kg ha^{-1}). Similarly, lowest soil residual NO_3-N was observed with CS × NT (15.2 kg ha^{-1}) under controlled drainage, CC × CH (22.8 kg ha^{-1}) under conventional drainage and CC × ST (19.9 kg ha^{-1}) under no drainage (Figure 1.1).

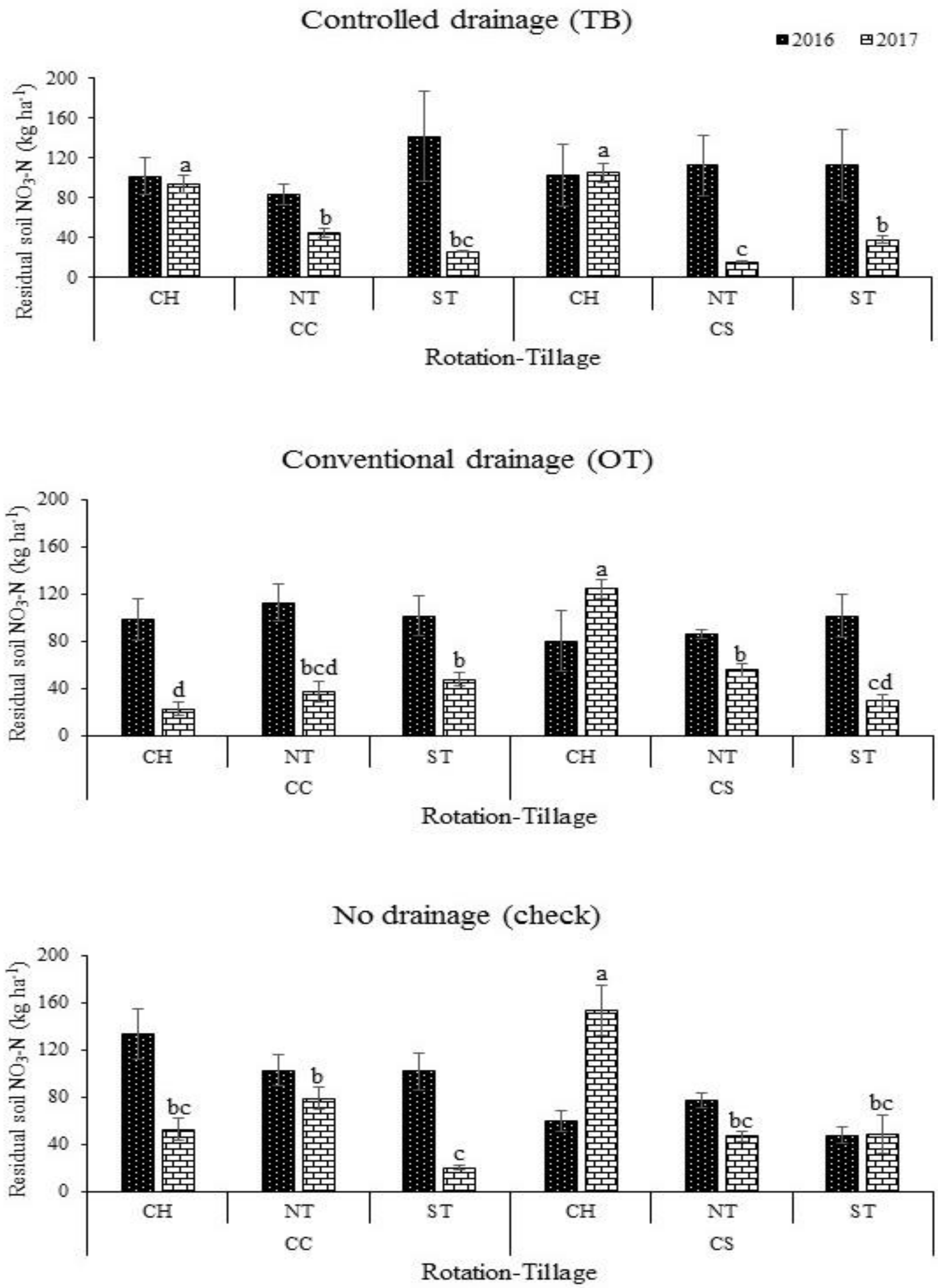

Figure 1.1. Residual soil nitrate (NO_3-N) (kg ha^{-1}) in corn plot for drainage (Check-no drainage; OT-conventional drainage; CD-controlled drainage), under rotation (CS-corn soybean; CC-continuous corn) and tillage (CH-chisel; NT-no till; ST-strip till) method for 2016 and 2017 growing season. Vertical bars in diagram represent standard error at n=3. Same letter above bar are not significantly different at P<0.05 according to LSD test

In soybean plots, only drainage had significant effect on residual soil NO_3-N during 2017 growing season. Highest residual soil NO_3-N was observed with OT (20.5 kg ha^{-1}) and lowest with no drainage (5.6 kg ha^{-1}) (Table 8).

Discussion

Crop yield

Subsurface drainage was not effective for increasing corn and soybean yield in the four-year study (2014-2017). This was likely due to lower than average precipitation in June and July. This is consistent with Helmers et al. (2012) and Schott et al. (2017) where they observed corn and soybean yields to be higher in undrained plots compared to OT and CD during low rainfall in the months of July and August. Kladivko et al. (2005) found lower corn yield in check (no drainage) for only 3 years out of 10, where the remaining years had no differences between drained and non-drained plots. However, our results are in contrast with Skaggs and Schilfgaarde (1999).

CH had higher yield over ST and NT, but the differences decreasing over the four years of study (2014-2017). Dickey et al. (1983) and Randall et al. (1996) reported that CH and moldboard plow recorded high yields on moderately to somewhat poorly drained soils as compared to NT; whereas, other researchers found no tillage effects on soils varying from poorly to well drained (Dick et al., 1991; Vepraskas et al., 1992; Vetsch and Randall, 2002).

Porter et al. (1997) reported that corn and soybean yield was 16% higher when grown in rotational system. Similar results of 18 and 37 % greater corn yield for rotation were observed in Wisconsin and Nebraska, respectively (Peterson and Varvel, 1989; Pedersen and Lauer, 2003). Introduction of legume crops change residual soil N for next crop (corn) and aids in reducing various biotic factors (insects and pathogens) on crop (Andow, 1983).

Planting corn after soybean (CS) with CH increased corn yield in three growing seasons (2015-2017) which is to results in Peterson and Varvel (1989), Varvel (1994), and West et al. (1996). Corn-soybean rotation is effective in preventing deep NO_3-N leaching than continuous corn (Katupitiya et al., 1997), reduces stress from pests (Boosalis and Doupnik, 1976), and input costs are less with rotation (Foltz et al., 1995). Interaction of drainage × rotation showed variable response over our four-year study, but CS with different drainage (OT, CD and Check) generally performed better than CC. No drainage with CH enhanced corn and soybean yield. This shows that tillage systems impact agronomic productivity over drainage which is affected by weather condition (Dick et al., 1991; Hellin and Schrader, 2003). In the interaction among drainage, rotation and tillage, corn yields were generally were higher when rotated with soybean and had CH, but varied with their combined drainage response for 2014-2016 growing seasons. Interaction among the factors depend upon weather conditions (rainfall and temperature) which impact tillage and drainage treatment (Dick et al., 1991; Hellin and Schrader, 2003).

Residual soil nitrate

The difference in soil NO_3-N content after harvest might be due to different rainfall pattern in 2016 and 2017. The higher soil NO_3-N under CH compared to NT and ST might be due to N mineralization (Levanon et al., 1993) or greater immobilization or denitrification (Randall and Iragavarapu, 1995) in the CH system. No drainage with CS rotation had higher soil NO_3-N compare to OT under CC, which could be due to leaching of soil nitrate through subsurface drainage (Woli et al., 2010). Similarly, no drainage with CH had higher residual soil NO_3-N that could be due to reduced leaching (Woli et al., 2010) and increased N mineralization (Levanon et al., 1993). Interaction of drainage × rotation × tillage shows higher soil NO_3-N with no drainage, CS with CH; which might be due to reduced leaching, N mineralization and weather condition (low rainfall). Under soybean plots, OT had higher residual soil NO_3-N that might be due to more nitrogen used by soybean from check plots leading to higher soybean yield (Jaynes et al., 2001).

Conclusion

Results from the four-year study indicate that effect of subsurface drainage is highly dependent on growing season precipitation. No drainage performed better than subsurface drainage (controlled or conventional) in three out of four years due to low rainfall compare to the 30-year average. This shows that in Fargo clay soil, installation of subsurface drainage is likely beneficial in wet years only. The decrease in yield gap between no-till and chisel plow over four years shows that conservation tillage will require more time to show positive effects. Continuous corn in poorly drained soil with no-till is not advisable due to low yield and high residual nitrate. There was no difference in soybean yield at different drainage due to less than average rainfall and chisel plow was productive over no-till and strip tillage in plot with corn residue. Controlled drainage is preferable compared to conventional drainage to maintain optimum soil moisture when rainfall deviated to dry conditions as compared to the 30-year average. Residual soil nitrate was higher in no drainage with chisel plow that shows that drained plot probably had lost some amount of NO_3-N. These results suggest that subsurface drainage did not improve corn and soybean yield due to lower than average rainfall, but interaction between drainage, crop rotation and tillage has significant effect on crop yield. Short-term study of soil water management in Fargo clay soil suggested there is need of detailed and long-term experiment to understand interaction among climate and crop management practices.

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CHAPTER 2. EFFECT OF SUBSURFACE DRAINAGE SPACING AND DEPTH ON CROP YIELD IN A SMECTITIC CLAY SOIL

Abstract

Soil water management is key to maintain and improve crop production in poorly-drained, frigid clay soils. However, drainage-design recommendations for such soils, as in the Red River Valley of the North, continue to evolve. The objective of this three-year (2015-17) study was to evaluate subsurface drainage spacing (9, 12, and 15m) and depth (0.9 and 1.2m) on corn (*Zea mays*), soybean (*Glycine max L.*) and sugarbeet (*Beta vulgaris*) yields and residual soil nitrate-nitrogen (NO_3-N) contents. Subsurface drain spacing significantly affected corn, soybean, and sugarbeet yields in some, but not all, of the three years; corn in 2015 and 2017, soybean in 2015, and sugarbeet in 2017. Moreover, mixed results were observed for corn. When averaged across 3-years, the 9m spacing produced the highest corn yields and lowest with 15m spacing. This was also observed during 2015; the wettest year. However, the wider spacing (15m) yielded the highest corn during 2017; the driest year. Similarly, sugarbeet yields were highest with the 15 m spacing during 2017. Soybean yield was highest with 9m subsurface spacing during 2015 and when averaged across all three years. In contrast to drain spacing, the drain depth had no effect on corn and soybean yields, except for sugarbeet where the 1.2m depth yielded higher than the 0.9m depth. Drainage design affected residual soil NO_3-N only in 2016 for corn and sugarbeet. Narrower drain spacing (9m) had higher residual soil NO_3-N in corn; whereas for sugarbeet, it was 12m spacing. These data indicate that narrower spaced subsurface drains in poorly-drained, frigid clay soils may increase corn and soybean yields during wet years, but that wider spacing may be beneficial during relatively dry years. Therefore, producers should consider the frequency of wet to dry years for their region while choosing a subsurface drainage system.

Key words: residual soil NO_3-N; drain spacing; depth

Introduction

Subsurface drainage is a common water management practice to remove excess water from poorly drained soils in the Northern Great Plains, USA; permitting timely fieldwork, better soil aeration and crop establishment, increases nutrient available, and crop yields (Lal and Taylor, 1970; Zucker and Brown, 1998). Soil water content and amount of water stored in soil profile is affected by water table height which can be altered by subsurface drainage (Madramootoo et al., 1994; Skaggs and Chescheir, 2003). However, key factors for subsurface drainage design (drain spacing and depth) include soil permeability, cropping system, degree of surface drainage, climate, tillage practices, rainfall pattern, and water table depth (Kladivko et al., 2004; Wright and Sands, 2001). Narrower drain spacing is known to produce higher drainage amounts. For instance, Kladivko et al. (1991) reported 6-27 % water-equivalent of total incident rainfall was removed through subsurface drainage on a poorly-drained Clermont soil in Indiana depending on drain spacing and year. They observed that the amount of water drained from soil profile decreased with increases in drain spacing. Researchers suggest drain spacing need to be assessed over several years (Kladivko et al., 1991). Deeper drains are often increase drainage amounts. Helmers et al. (2012) and Schott et al (2017) observed 40 % reduction of annual drainage volume at a drain depth of 0.76 m as compared to 1.20 m. However, mixed results can occur when low-permeability soil layers, overlying or underlying the drains, are present (Goins, 1956; Hoover and Schwab, 1969).

Regarding crop yields, subsurface drainage generally improves yields during wet years. Research conducted by Lal and Fausey (1998) in central Ohio showed that crop yield increased with decreasing subsurface drain spacing. Moustafa et al. (1987) found 39 and 16 % increases in crop yields with 12.5 m and 25 m drain spacing, respectively, as compared with 50 m drain spacing in a clay soil. Schott et al. (2017) reported five-year-average corn and soybean yields for undrained treatments were 6 % less than conventional drainage; whereas, controlled drainage did not reduce corn yields during 2011 to 2015 in Iowa.

Studies also show that subsurface drainage can also increase organic matter mineralization and nitrification, decrease denitrification, and create direct conduit for soluble nitrogen (N) movement (Randall and Goss, 2001; Dinnes et al., 2002). Large subsurface drain flows and NO_3-N losses are typically associated with wet years (Daigh et al., 2014). However, smaller differences, in NO_3-N losses, between wet and dry years are expected when N fertilizer rates are reduced (Davis et al., 2000; Moriasi et al., 2013). Early studies shows subsurface drainage increases NO_3-N loss from fertilized crop fields, (Baker and Melvin, 1994; Logan et al., 1994; Soenksen, 1996) which decreased nitrogen availability for crop growth during the following year's crop. Randall and Iragavarapu (1995) also observed subsurface drainage to decreases in residual soil NO_3-N from unfertilized crops. Cooke et al. (2002) found direct correlation between decreased subsurface flow, decreased subsurface drain depth, and decreased NO_3-N loss. Subsurface drain depth also had greater effect than subsurface spacing on phosphorous loss through subsurface drainage; indicating subsurface drainage depth management can be efficient practice to mitigate soil phosphorous loss (Tan and Zhang, 2014). In a long term simulation study, Davis et al. (2000) indicated that shallower drain depth reduce NO_3-N losses to a greater extent than wider drain spacing when compared with six different drain spacing and three drain depth. Reduction of 20% in annual drainage volume and NO_3-N was observed with drainage depth of 0.90 m compared to traditional depth of 1.20 m during a six year study in south central Minnesota (Sands et al., 2008). A range of spacing and depth can result in similar drainage volumes and NO_3-N losses; however, wider spacing reduce yield due to prolonged water-stress condition between the drainage laterals (Nangia et al., 2010). Hofmann et al. (2004) observed highest corn yields and lowest daily drainage water NO_3-N concentrations under 20 m spacing indicating that wider spacing's might provide insufficient drainage.

The objective of this study was to determine the effect of drainage designs on crop yields and residual soil NO_3-N in a poorly-drained, frigid, smectitic clay soil (Fargo soil series) in the Red River Valley of the North, where subsurface drainage is rapidly being adopted by agricultural producers. Specifically, this study evaluates subsurface drain spacing of 9, 12 and 15 m at two subsurface depths of 0.9 and 1.2 m on of a corn-sugarbeet-soybean rotation in North Dakota. This region has higher clay contents, annual frozen soil depths, and days of frozen soil than what is typically reported in subsurface drainage studies.

Material and methods

Site description and experimental design

A field trial was conducted for three growing seasons (2015-17) near Casselton, North Dakota (46°49'25.03''N, 97°13'5.70''W) on a Fargo silty clay soil (fine, smectitic, frigid Typic Epiaquerts) (Soil Survey Staff, 2013). Drain drains were installed in 2013. Corn-sugarbeet-soybean rotations were followed along three strips every year. The experimental design consist of three-drain spacing (9, 12, 15 m) and two drain depths (0.9 and 1.2 m).

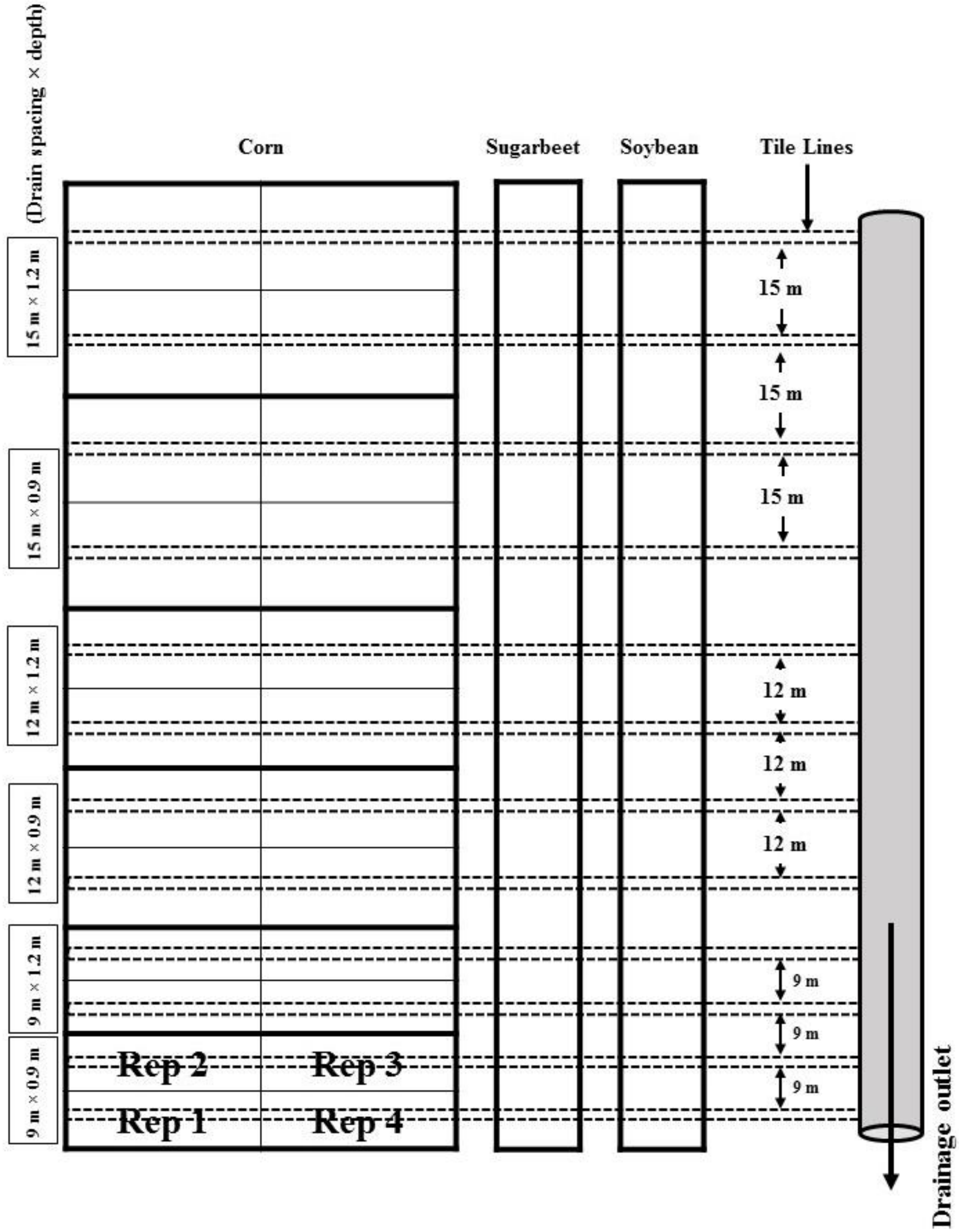

Figure 2.1. Experiment layout consisting three crops with three-drain spacing (9, 12, 15 m) at two depths (0.9, 1.2 m) in 2016 growing season.

The field experiment was laid out in complete block design with four pseudo-replications. Individual plot dimension was varied from 9 m by 3.35 m to 15 m by 3.35 m, which depend upon drain spacing (Figure 2.1). A 9 m gap was maintained between each treatment. Urea was applied as source of N at 179.3 kg N ha^{-1} for corn and 146 kg N ha^{-1} for sugarbeet in the last week of September after each year's harvest that was adjusted to residual inorganic nitrogen for 0-0.6 m. No fertilizer was applied for soybean crop. All three strips received chisel plough using Kongskilde Triple K field cultivator that has S-tine shank and double spiral roller behind at depth of 12 cm in fall after harvest and field cultivator was used to smooth soil surface prior to planting in spring. Roundup Ready soybean (Mustang 0443), corn (Dekalb C39-27Ri13) and sugarbeet (Crystal 093) cultivars were planted at 415,000; 84,000 and 148,200 plants per ha^{-1} respectively, using 0.56 m wide seed drill every year during the first week of May. For controlling weeds, Roundup (Isopropylamine salt of glyphosate a.i.) 25 ml liter^{-1} and Class act (water conditioning agent) 10 ml liter^{-1} was mixed and sprayed on last week of May and third week of June every year. To control rhizoctonia root rot in sugarbeet, Quadris (azoxystrobin) at the rate of 73 ml liter^{-1} was applied at the 4 to 6-leaf stage and again 3 weeks later. Similarly, to control cercospora leaf spot in sugarbeet, three fungicides, Inspire® (difenoconazole), Topsin® (thiophanate methyl), and Headline® (pyraclostrobin), were applied at the rate of 512 ml litre^{-1}, 555 ml litre^{-1}, and 730 ml litre^{-1}, respectively,

Sugarbeet were harvested on the first week of September every year. Tops of sugarbeet were removed using defoliator and middle two rows of roots were harvested using sugarbeet mechanical harvester. Sugarbeet root samples were collected from each plot and sent to American Crystal sugarbeet lab (Grand Forks, ND) for measuring tare percentage that was used to calculate actual beet yield (Mg ha^{-1}) and sugar quality. At physiological maturity, the middle three rows of each plot were harvested using the small plot combine harvester on the last week of September for soybean and third week of October for corn every year. The grain yield (Mg ha^{-1}) for soybean and corn was calculated using 14% moisture content.

Measurement of residual soil NO_3-N content

To determine residual soil NO_3-N content, intact soil cores of 2 cm diameter were collected to a depth of 0-15 cm and 15-60 cm from each plot at harvest. Composite soil sample was prepared using two soil cores from each plot and was transferred to laboratory at 5°C, and stored at -18°C until analysis within a week. After thawing and homogenizing frozen soil, 6.5 g of moist soil was extracted with 25 mL of 2M KCl (1:5 soil extractant ratio) after shaking for 30 minutes (Maynard et al., 2008). Timberline TL2800 Ammonia Analyzer (Timberline Instruments, CO, USA) was used to analyze KCl extract for residual soil NO_3-N. Separately weighed subsamples of soil for both depths were used to determine soil moisture content and bulk density using gravimetric method. Inorganic nitrogen concentration was multiplied with bulk densities of respective soil depth to express them weight on area basis (kg ha^{-1}). Total inorganic N for both depths (0-15 and 15-60 cm) were summed to obtain total inorganic N content for 0-60 cm depth.

Water table depth

Water table depths [one for each treatment for two crops (soybean and corn)] were measured during 2016 and 2017 growing season. Wells were 1.22 m deep and CTD-5 sensors (Decagon Devices Inc., Pullman, WA) were inserted in wells for monitoring water level in ground water. Observation-wells were continuously monitored for the water level at every one-hour using CTD-5 sensors and Em50 series data logger throughout the production season. Sensors in the experimental plots were installed after planting and removed before crop harvest.

Statistical analysis

Analysis of variance (ANOVA) was used to test effects of drain spacing and depth on crop yields and residual soil nitrate using PROC ANOVA. Drainage spacing and depth were fixed effects and replicates were random. Data were analyzed separately for each year and crop with Statistical Analysis System (SAS) software (version 9.4 SAS, 2013). Mean separation was done using Fisher's protected least significant difference at $P<0.05$. The trend of water table change was observed for two crops at different drain spacing and depth for two years.

Results

Climatic conditions and water tables

Rainfall during the 2015-17 growing seasons is presented in Figure 2.2. Rainfall was 16, 22, 45 % less than 30-years average for 2015-17 growing season, respectively. Monthly rainfall comparison shows May and June of 2015 had double rainfall compare to 2016 whereas opposite trend was observed for remaining growing season (July to September). The year 2017 was driest year in decade with rainfall during May to September being 22, 39, 37, 50 and 69 mm, respectively. Average air temperature at study site did not substantially deviate from 30-year average. After crops were planted, only two rainfall events (July, 2016 and June, 2017) caused water table to rise above the depth drain depths. In both drainage events, water tables were above drain depths for over 3 wks.

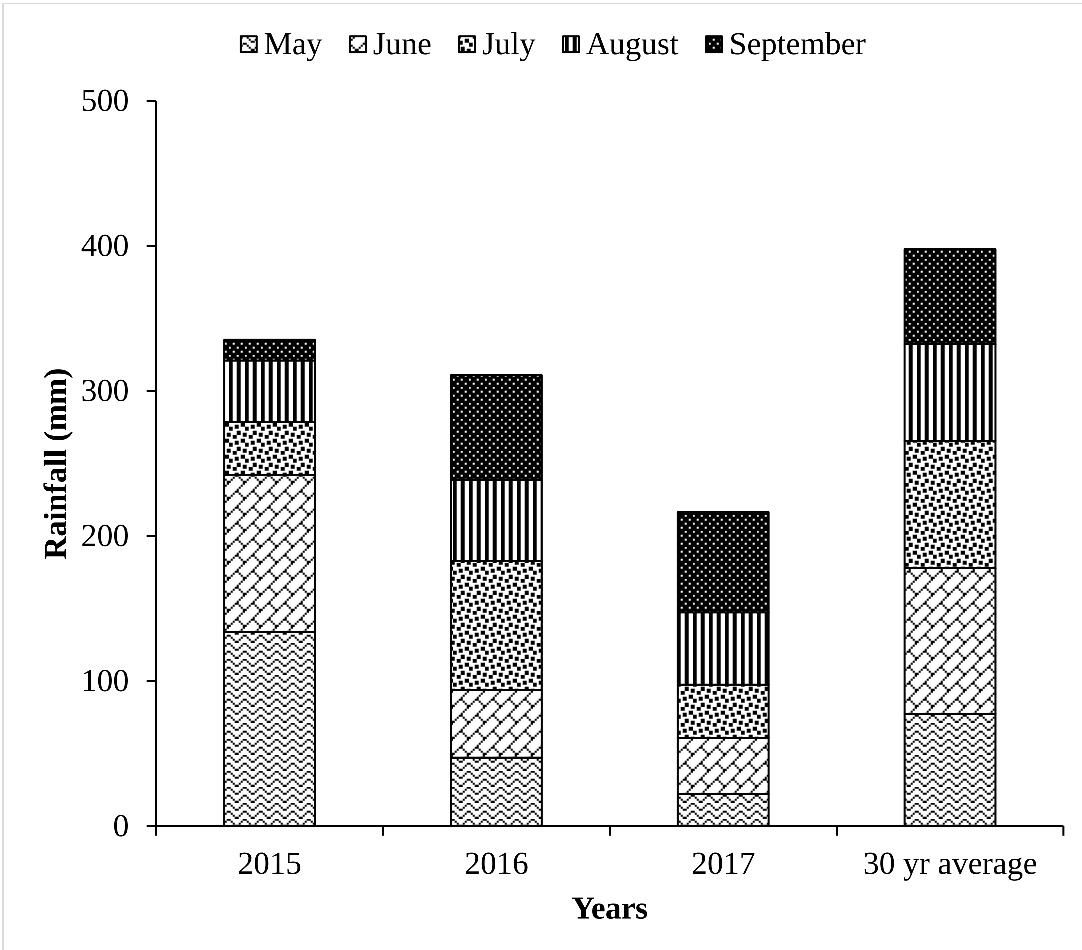

Figure 2.2. Monthly total precipitation (mm) for 2015-17, as well as the 30-year average at research site near Casselton, North Dakota.
Source: NDAWN. North Dakota Agricultural Weather Network. 2017. North Dakota State University, Fargo, ND

Crop yield

Main effect of corn yield to drain spacing was significant for 2015, 2017, and the 3-year average (Table 2.1). Corn yield response to drain spacing was not consistent for the three different growing seasons. Corn yield was highest with 9 m drain spacing for 2015 and the 3-year average (14.3 and 13.1 Mg ha^{-1}, respectively), with the lowest yields observed with the 15 m drain spacing.

Table 2.1. Main and interaction effects crop yields to drain spacing (9, 12, 15 m) and depth (0.9, 1.2 m) for corn, soybean and sugarbeet for three growing years and average over three growing season

	Corn				Soybean				Sugarbeet			
Spacing (m)	**2015**	**2016**	**2017**	**3-year average**	**2015**	**2016**	**2017**	**3-year average**	**2015**	**2016**	**2017**	**3-year average**
	-- Yield (Mg ha^{-1}) --											
9	14.30 a¶	13.69	11.38 b	13.13 a	2.38 a	3.44	3.55	3.12 a	65.88	68.21	74.81 a	69.65
12	10.22 b	14.43	12.08 ab	12.24 b	2.18 ab	3.61	3.63	3.14 a	63.78	68.24	72.43 b	68.15
15	9.05 b	13.31	12.41 a	11.59 b	2.07 b	3.27	3.4	2.91 b	66.02	69.15	75.46 a	70.21
P<F	*0.001*	*0.434*	*0.049*	*0.003*	*0.037*	*0.075*	*0.219*	*0.012*	*0.463*	*0.961*	*0.004*	*0.371*
Depth (m)												
0.9	11.53	13.75	11.89	12.39	2.27	3.43	3.59	3.09	63.48 b	67.42	74.69	68.53
1.2	10.86	13.87	12.03	12.25	2.14	3.45	3.46	3.02	66.98 a	69.65	73.78	70.14
P<F	*0.3*	*0.868*	*0.664*	*0.656*	*0.156*	*0.822*	*0.216*	*0.2*	*0.046*	*0.481*	*0.172*	*0.195*
Spacing × depth (m × m)												
9 × 0.9	14.81	13.7	11.24	13.25	2.32	3.48	3.53	3.11	66.59	69.43	74.53 bc	70.18
9 × 1.2	13.81	13.69	11.53	13.01	2.43	3.41	3.56	3.13	65.18	66.99	75.09 b	69.09
12 × 0.9	10.24	13.98	11.78	12.00	2.30	3.50	3.82	3.21	60.73	63.42	71.28 d	65.14
12 × 1.2	10.21	14.88	12.37	12.49	2.06	3.72	3.45	3.08	66.84	73.05	73.59 bcd	71.16
15 × 0.9	9.53	13.58	12.64	11.92	2.20	3.31	3.43	2.98	63.12	69.40	78.26 a	70.26
15 x 1.2	8.56	13.04	12.18	11.26	1.94	3.23	3.37	2.85	68.91	68.91	72.66 cd	70.16
P<F	*0.775*	*0.703*	*0.397*	*0.309*	*0.181*	*0.467*	*0.3*	*0.495*	*0.132*	*0.262*	*0.003*	*0.057*

¶ Values within a column for a period followed by same letter are not significantly different at P<0.05 according to LSD test

However, in 2017, yield was highest with 15 m drain spacing (12.4 Mg ha^{-1}), with the lowest yields observed with the 9 m spacing. Main effect of drain depth and the interaction between drain spacing and depth were not significant for any year or for the 3-year average.

Main effect of soybean yield to drain spacing was significant for 2015 and the 3-year average (Table 2.1). Similar to corn yields, the soybean yield was highest with 9 m drain spacing, but also similar to the 12 m drain spacing, for 2015 and the 3-year average, with the lowest yields observed with the 15 m drain spacing. Main effect of drain depth and the interaction between drain spacing and depth were not significant for any year or for the 3-year average.

Main effect of sugarbeet to drain spacing was significant for 2017, which also had a significant drain spacing by drain depth interaction (Table 2.1). Main effect of sugarbeet yield to drain spacing resulted in 75.5, 74.8 and 68.2 Mg ha^{-1} yields with the 15, 9 and 12 m drain spacing, respectively, for 2017. The interaction of drain spacing by drain depth was mostly caused by the 15 m×0.9 m combination causing significantly higher sugarbeet yields than all other treatments in 2017. Main effect of sugarbeet to drain depth was significant for 2015, where sugarbeet yields were higher with 1.2 m drain depth as compared to the 0.9 m drain depth (67.0 and 63.5 Mg ha^{-1}, respectively).

Residual soil NO_3-N content

Residual soil NO_3-N was significantly by drain spacing by depth interaction for corn and sugarbeet in 2016 (Figure 2.3). Highest residual soil NO_3-N of 83.1 kg ha^{-1} was with 9 m×1.2 m and the lowest residual soil NO_3-N of 23.0 kg ha^{-1} was with 12 m×1.2 m for corn. Whereas, the highest residual soil NO_3-N of 88.2 kg ha^{-1} was with 12 m×1.2 m and the lowest residual soil NO_3-N of 61.8 kg ha^{-1} was with 15 m×0.9 m for sugarbeet. No effect was observed for soybean.

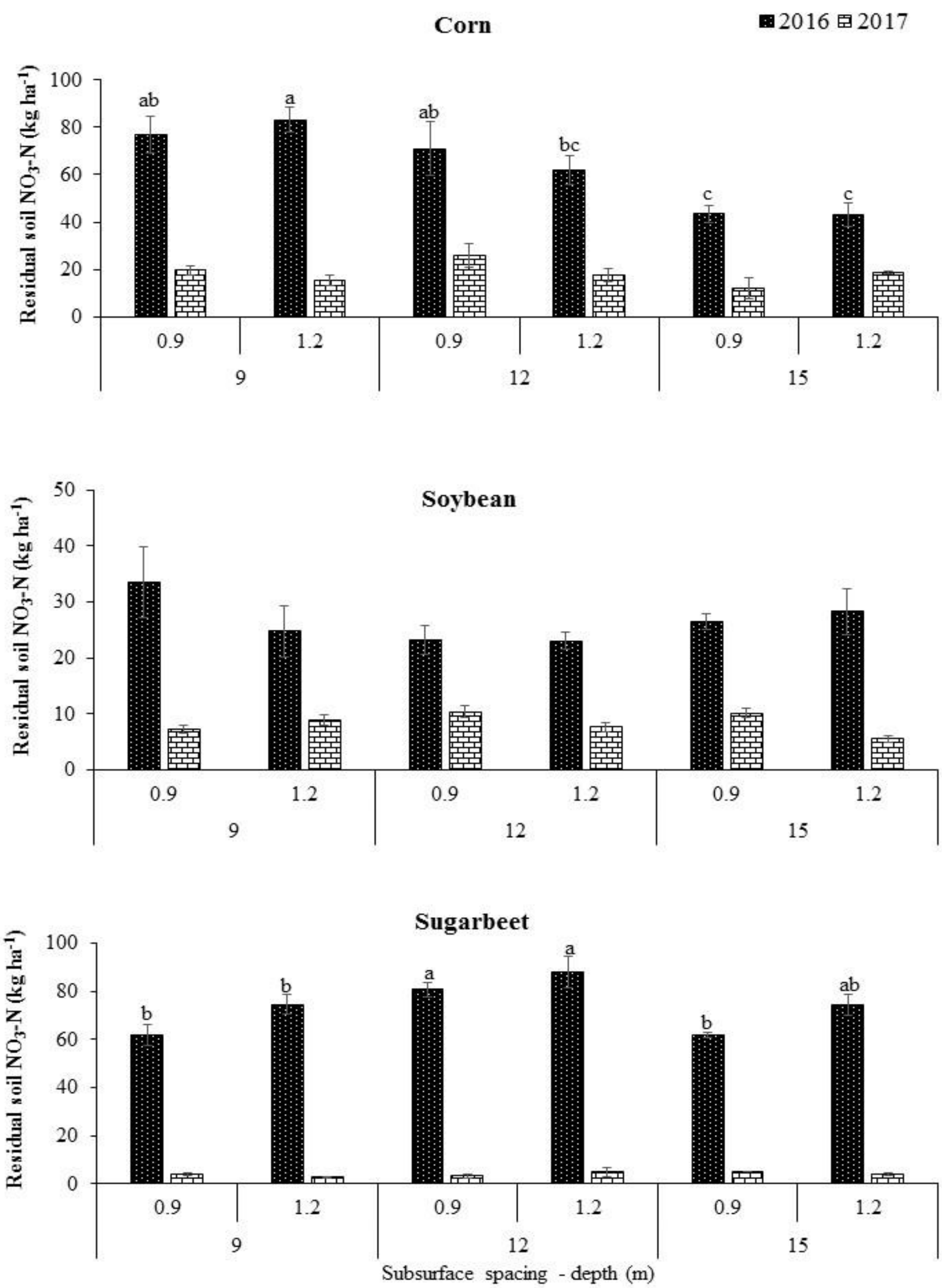

Figure 2.3. Residual soil NO_3-N (kg ha^{-1}) for corn, soybean and sugarbeet at drain spacing (9 m, 12 m, 15 m) and depth (0.9 m, 1.2 m) for 2016 and 2017 growing season. Vertical bars in diagram represent standard error at n=3. Same letter above bar are not significantly different at P<0.05 according to LSD test.

Discussion

Crop yield

The corn yield response depends on rainfall of that growing season. For instance, the narrower drain spacing of 9 m resulting in significantly higher corn yields during the wet year of 2015; whereas the widest drain spacing of 15 m resulted in significantly higher corn yields during the driest year of 2017. Subsurface drainage provides more access to remove excess waters above field capacity that may otherwise cause poor aeration for seedlings. Since plant available water is typically assumed to exclude water held between saturation and field capacity, the removal of waters above field capacity are thought to have no consequence to crop production. However, this assumption is not valid in poorly drained, slow permeable clay soils where soil water held between saturation and field capacity do not rapidly contribute to deep percolation, and is therefore available to the plant. By installing subsurface drains, giving access to readily drain these slow moving waters above field capacity, this fraction of soil water is now allowed to readily drain and consequently become unavailable to plants. In years with drought conditions after snowmelt, this could potentially lead to less total water available for the plants during the growing season and a reduction in crop yield, as observed in 2017 in the present study. Although this is rarely documented in the scientific literature, most publications report on studies from lower clay content soils and in more humid areas than that of the Red River Valley of the North. The slower drainage rate of the 15 m spacing may have provided a better balance between adequate drainage while maximizing water accessible for plant uptake. Corn yield was not affected by drain depth and seems to be only function of spacing in the frigid, smectitic clay soil. The impact of excess soil moisture of corn yield at early stage has negative effect on corn yield that was observed in first year of this study. The difference in rainfall pattern in three years of study shows mixed results in drain designs effect to corn yield. These results are consistent with other studies conducted on drain spacing and depth (Moustafa et al., 1987; Sands et al., 2008; Schwab et al., 1957). There was no difference in corn yield at different drain spacing (5 m, 10 m, 20 m) in long-term study conducted by Kladivko et al. (2004). Brouder et al. (2005) found little difference in corn yield (7.8, 8.0 and 7.9 Mg ha^{-1}) for drain spacing of 10, 20 and 30 m, respectively.

Soybean yield was higher under 9 m drain spacing in 2015, when the most rainfall was observed among the three years for the months of May and June (Figure 2), as well as when averaged across all three years. This was expected since closer drain spacing results in higher drainage coefficient and faster removal of excess water. Wider drain spacing causes yield reduction due to prolonged water-stress condition in wet years. Overall, soybean yields had less sensitive to drainage design than corn.

Similar to corn during the dry year of 2017, sugarbeet yield was higher with wider drain spacing (15 m) for 2017. In Iowa, Sands et al. (2013) observed 29 % reduction in sugarbeet yield when water table stays 38 to 51 cm below surface for extended periods during growing season. In the present study, the one rainfall event that caused water table to rise above the drains, produced water table between 20 and 50 com for less than 1 wk. Sugarbeet yield response to drainage management can vary with the amount and the pattern of precipitation received during the growing season. These results are in line with study conducted by Awale et al. (2015), Chatterjee et al. (2015) in North Dakota and Nash et al. (2015) in Missouri.

Residual soil nitrate

Residual soil NO_3-N depends mostly upon how much of NO_3-N is leached out through subsurface drainage and gasses losses via denitrification and ammonia volatilization. Within 0-

60 cm depth, residual soil NO_3-N content decreased with wider spacing indicating increase in N uptake and increase in N losses through denitrification for corn. For sugarbeet crop, the residual soil NO_3-N increased with wider spacing that might be due to decrease in N leaching (NO_3-N) loss due to wider spacing in 2016. There was no difference in residual soil NO_3-N for soybean because no additional nitrogen fertilizer was supplied for soybean crop for both years. The wet field most likely caused nitrogen lost by denitrification and ammonia volatilization rather than leaching through drain drainage in close spacing in clay soil. These results are consistent with other studies conducted on soil NO_3-N at different drain spacing and depth (Dinnes et al., 2002; Kladivko et al., 2004; Madramootoo et al., 1994; Drury et al., 2014). Similar results were also observed by Awale et al. (2015) and Chatterjee et al. (2015) in sugarbeet.

Conclusion

This three-year study revealed that drain spacing and depth determination depends upon rainfall patter and crop cultivated for a corn-sugarbeet-soybean rotation on poorly-drained, frigid, smecitic clay soils in the Red River Valley of the North. Crop yields were highest with narrower drain spacing in wet year and wider drain spacing in dry year. In wet years, narrower drain spacing produced higher yields for corn and soybean; whereas, in dry years wider drain spacing produced higher yields for corn and sugarbeet. Producers should consider the frequency of wet to dry years for their region while choosing a subsurface drainage system. However, the 3-year average yields tended to be higher with narrower drain spacing (9 m), indicating a potential long-term benefit for crop yield when using narrower drain spacing. Few differences in crop yield occurred when compared with drain depths (0.9 and 1.2 m). This research provides important information to producers who are considering installing drain drainage in the clay soils of the Red River Valley of the North.

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CONCLUSIONS

Our results from both studies shows crop yield under different drainage, tillage and rotation at different drain spacing and depth is highly dependent on growing season precipitation. No drainage performed better than subsurface drainage (controlled or conventional drainage) in three out of four years due to low rainfall compare to 30-year average. This shows that in Fargo clay soil, subsurface drainage is likely beneficial in wet years only. Conservation tillage takes more time to show positive result that was observed with decreasing yield gap between no-till and chisel plow over four years. Continuous corn with no-till is not advisable in poorly drained clay soil due to low yield and residual soil NO_3-N. Controlled drainage is preferable compared to conventional drainage to maintain optimum soil moisture when rainfall deviated to dry conditions as compared to the 30-year average. Residual soil nitrate was higher in no drainage with chisel plow that shows that drained plot probably had lost some amount of NO_3-N. These results suggest that subsurface drainage did not improve corn and soybean yield due to lower than average rainfall, but interaction between drainage, crop rotation and tillage has significant effect on crop yield.

The three-year study on drain spacing and depth determination revealed that crop cultivated for corn-sugarbeet-soybean rotation on poorly-drained, frigid, smectitic clay soils in Red River Valley of North depends on rainfall pattern of cultivated season. Crop yields were highest with narrower drain spacing in wet year and wider drain spacing in dry year. In wet years, narrower drain spacing produced higher yields for corn and soybean; whereas, in dry years wider drain spacing produced higher yields for corn and sugarbeet. Results shows that farmers should consider frequency of wet to dry years for their region while choosing subsurface drain spacing and depth. Short-term study of soil water management in Fargo clay soil suggested there is need of detailed and long-term experiment to understand interaction among climate and crop management practices.