UTILIZATION OF MANAGED SUBSURFACE DRAINAGE TO INCREASE CORN AND FORAGE YIELDS AND REDUCE NITROGEN LOSS IN POORLY-DRAINED, UPLAND AND BOTTOMLAND SOILS

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By

PATRICK R. NASH

Dr. Kelly Nelson, Dissertation Co-Supervisor
Dr. Peter Motavalli, Dissertation Co-Supervisor
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The undersigned, appointed by the dean of the Graduate School, have examined the thesis entitled:

UTILIZATION OF MANAGED SUBSURFACE DRAINAGE TO INCREASE CORN AND FORAGE YIELDS AND REDUCE NITROGEN LOSS IN POORLY-DRAINED, UPLAND AND BOTTOMLAND SOILS

presented by Patrick R. Nash

a candidate for the degree of Doctor of Philosophy of Science in Soil, Environmental and Atmospheric Sciences

and hereby certify that, in their opinion, it is worthy of acceptance.

Dr. Kelly Nelson

Dr. Peter Motavalli

Dr. Robert Kremer

Dr. Stephen Anderson

DEDICATIONS

I dedicate my dissertation work to my family and friends. Special thanks go to my parents, Steve and Mary Nash, for their endless love and support, as well providing me with wonderful life experiences. My brother, Jon, for providing me the support and motivation needed to complete my dissertation work.

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CHAPTER 1

LITERATURE REVIEW

Poorly-Drained Soils

Introduction

Poorly-drained soils are classified based on a high water table which may be due to low overall hydraulic conductivity and slow permeability (Madramootoo, 1999). Inadequate soil drainage leads to extended periods of soil saturation that reduces soil aeration, biological activity, and increases the potential for soil compaction (Evans and Fausey, 1999; Daum, 2014). The drainage capacity of soil is highly related to soil texture, structure, bulk density, layering, and depth to the impervious layer (Madramootoo, 1999). Generally, as soil texture gets finer (sand to clay particles), pore size, and hydraulic conductivity decrease which lowers the drainage capacity (Whiting et al., 2011). However, soils with less developed soil structure are comprised of more micropores which results in a more tortuous water flow path and poorer soil drainage regardless of the soil texture. Soils contain horizons which are layers of soil with varying physical and chemical properties that can also impact a soil's drainage capability due to differences in hydraulic conductivities and abrupt transitions in soil texture among horizons. The drainage capacity of soil is often controlled by the layer with the lowest hydraulic conductivity (Franzmeier et al., 2001).

Saturated soil conditions that are common with poorly-drained soils can make crop production challenging due to issues that arise in timeliness of field operations, workability of soil, increased compaction with traffic on wet soils and soil aeration (Skaggs and Van Schilfgaarde, 1999). Therefore, selecting management practices that minimize the occurrence of saturated soil conditions or mitigate its deleterious effects on plant growth, such as poor soil aeration are essential to obtaining maximum crop yield potential.

Claypan Soils

Claypan soils, such as a Putnam silt loam (fine, smectitic, mesic Vertic Albaqualfs), have a subsurface soil horizon as shallow as 36 cm and as deep as 53 cm (Watson, 1979). The claypan layer is high in clay content and has low permeability (Jung et al., 2006; Myers et al., 2007). Leaching of water through the claypan layer is minimal (K_{sat} <0.01 µm sec) (Watson, 1979) and results in a seasonal perched water table, when rainfall exceeds the rate of evapotranspiration, as is common during the spring and winter months in the region (Yeh et al., 1998). Claypan and claypan like soils comprise approximately 3.5 million ha of land in U.S., which are primarily located in Missouri and Illinois (USDA-NRCS, 2006). Row crop production is common on claypan soils (Watson, 1979), but extended periods of saturated soil conditions can reduce crop yields.

Bottomland Soils

Bottomland soils located in floodplains, such as Blackoar silt loam (fine-silty, mixed, superactive, mesic Fluvaquentic Endoaquolls) or Wabash silty clay (fine, smectitic, mesic Cumulic Vertic Endoaquolls) are deep, have moderate organic matter content, and high soil fertility (Watson, 1979). Unlike claypan and claypan-like soils, which are specific to regions, bottomland soils are widespread throughout the world. Soils located in floodplains have naturally high soil fertility due to sediment deposition and the formation of a deep surface horizon. Therefore, these soils can be high-yielding environments for row crop production. However, bottomland soils can be poorly-drained and experience saturated soil conditions due to high seasonal water tables, high clay content, and flooding; all of which can reduce crop yields.

Agricultural Production Issues Associated with Poorly-Drained Soils

Introduction

Excessive soil moisture common with poorly-drained soils can result in poor crop production. Low crop yields resulting from excessive soil moisture can be due to the inability to conduct field operations in a timely manner, inadequate soil aeration, and significant environmental losses of applied N (Evans and Fausey, 1999).

Timeliness of Field Operations

Delayed planting due to saturated soil conditions can negatively impact crop yields. A historical review of corn production in the Midwestern U.S. reported that yield typically increased with earlier planting dates (Kucharik, 2008). Yield response to planting date is generally due to day length, temperature, and soil moisture (Evans and Fausey, 1999). Planting earlier typically maximizes the period of time in which soil conditions are conducive for plant growth. Planting early can be increasingly important in regions with short growing seasons due to early frost (Seymour, 1986) and dryland production systems with limited soil water availability later in the growing season (Popp et al., 2002).

Closely related to planting date is tillage which can also be impeded by wet soil conditions. Tillage can allow for early planting by temporarily increasing soil aeration and incorporating surface residues, which may promote earlier warming of the soil and improve seedbed conditions (Bond et al., 1971; Erickson, 1982). Use of tillage to improve seedbed conditions at planting can be increasingly important in high clay soils (Popp et al., 2000).

Timing N applications to meet crop uptake needs and minimize N loss can be an effective management practice to increase N use efficiency (Samborski et al., 2009) and yields. Split N applications compared to a single N application have been reported to increase plant or grain N uptake and yields with corn (Abbasi et al., 2012), winter wheat (Gravelle et al., 1988), spring wheat (Stark and Tindall, 2013), forage oats, and rye (Cummins et al., 1965). Maximizing crop yields through optimal timing of N applications may not be possible with poorly-drained soils due to saturated soil conditions that can inhibit field operations. Therefore, application of N may instead be applied at one time in the fall or at preplant at a higher rate in order to compensate for the greater potential for loss of applied N and avoid potential trafficability issues during the growing season (Torbert et al., 1993).

Soil Aeration

Soil aeration is a measure of the air-filled porosity of the soil, which is a function of the total pore space minus the volume of water in the pore space. Poorly-drained soils can have low soil aeration due to high water-filled pore space. Low soil aeration can impact seed germination, root growth, shoot growth, and subsequent crop yields (Evans and Fausey, 1999; Benjamin, 2013). Fausey and McDonald (1985) reported that corn emergence was reduced 64 to 76% when flooding occurred for six consecutive days. The level below which germination and plant growth become dependent on oxygen concentration has been referred to as the critical oxygen concentration (Berry and Norris, 1949). Seed germination tolerance to low soil oxygen concentration varies among plant species and cultivars (Fausey et al., 1985; VanToai et al., 1988).

Plant root uptake of oxygen in the soil is required for aerobic respiration which is the process of converting sugars formed from photosynthesis into energy. This process is required for plant growth and other metabolic processes. Therefore, plant growth can be limited by a low oxygen concentration in the soil. Waterlogging of a soil can reduce diffusion of oxygen into the soil and oxygen concentration in the root zone can decrease below critical levels within hours (Mukhtar et al. 1990). Low soil aeration due to saturated soil conditions have been found to reduce root elongation, root depth, and root area in corn (Grable and Siemer, 1968; Baser et al., 1981) and soybean (Stanley, 1978). This impairment to roots can reduce a plant's ability to uptake water (McDaniel, 1995) and nutrients (Wolkowski, 1990).

Corn yield response to flooding or saturated soil conditions can vary due to duration and when the water stress occurred in relation to the plant growth development stage. At emergence, corn yield decreased 30, 50, and 55% after 2, 5, and 8 days of waterlogged soil conditions, respectively (Howell and Hiler, 1974). Torbert et al. (1993) reported that three days of saturated soil conditions at the V1 to V3 growth stage resulted in less than 1% reduction in corn yields, but seven days of saturated soil conditions reduced yield 5%.

Gaseous Nitrogen Loss

Extended periods of saturated soil conditions increase the potential for N loss through denitrification (Torbert et al., 1993). Denitrification is an anaerobic, microbial N transformation of nitrate to dinitrogen and nitrous oxide (N_2O) gas, which typically occurs at or near saturated soil conditions (Pilot and Patrick, 1972; Ryden and Lund, 1980). Applied urea and ammonium fertilizers must first be converted to nitrate through nitrification before denitrification loss can occur. Soil wetting and drying cycles can greatly impact denitrification loss as the presence of aerobic and anaerobic soil conditions are required for nitrification and denitrification to occur, respectively (Aulakh et al., 1991). Therefore, denitrification is directly linked to soil microbial activity (Six et al., 2004). The rate of denitrification has been reported to increase with temperature above 10 ^{o}C when nitrate-N is not limiting (Craswell, 1978; Sexstone et al., 1985).

Poorly-drained soils in agricultural production can have a deleterious effect on the environment due to high N inputs, potential for denitrification, and subsequent emissions of N_2O gas if N is not properly managed. Nitrous oxide, a greenhouse gas also linked to ozone depletion, has a global warming potential approximately 310 times that of carbon dioxide, and has an atmospheric residence time of approximately 120 years (Fields, 2004; Smith et al., 2007; Solomon et al., 2007). Soil N_2O emissions associated with agricultural practices is the largest source (69%) of soil N_2O emissions in the U.S. (USEPA, 2011). From 1990 to 2011, soil N_2O emissions related to agriculture increased 9% (USEPA, 2011). Due to the high potential for denitrification loss and subsequent N_2O emissions from poorly-drained soils, farmers can minimize negative effects on production and the environment by managing soils in ways that reduce the potential for gaseous N loss.

Environmental loss of applied N can limit availability of N for plants and subsequently reduce crop yields. The majority of applied N loss occurs through leaching of nitrate-N below the root zone in well-drained soils, while N loss through denitrification is typically of greater concern in poorly-drained soils (Allison, 1973).

Compared to well-drained soils, poorly-drained soils have a lower potential for nitrate-N leaching due to lower permeability, and increased potential for denitrification loss (Legg and Meisinger, 1982). Poorly-drained soils with a shallow impervious soil layer, such as claypan soils, can further increase the potential for denitrification loss, as the claypan greatly reduces the potential for N leaching (Blevins et al., 1996; Wilkinson et al., 2000).

Corn studies over a variety of climates, soil types, and management practices indicate that on average, soil N_2O gas emissions, a product of denitrification, rarely exceed 2% of applied N fertilizer (Drury et al., 2006; Halvorson et al., 2010b; Halvorson and Del Grosso, 2013; Venterea et al., 2010). However, N loss as N_2O gas from a claypan soil was found to consistently exceed 2% of applied N fertilizer and at times was as high as 4% with a surface application of urea fertilizers (Nash et al., 2012b). Additionally, Nash et al. (2012b) reported that strip-tillage with deep placement of controlled release N fertilizers did not reduce soil N_2O emissions compared to a surface application of N as was reported in other studies (Drury et al., 2006; Halvorson et al., 2011).

Impact of Subsurface Drainage on Agricultural Production

Brief History

Water, soil management and the need of drainage have been described as early as 160 B.C. and have been vital to human civilization (Beauchamp, 1987). Surface drainage management was introduced to North America by European settlers as early as the 1600's and was used to drain wetlands in order to increase the acreage of fertile and productive farmland (Dahl and Allord, 1997). Use of subsurface tile drainage to manage soil water in the United States began in 1838 by John Johnston, a Scottish immigrant who had knowledge of subsurface drainage and used it to improve soil drainage and wheat production on his farm in New York (Sands, 2009). More recently, increased knowledge of water flow in soils and the expansion and use of subsurface tile drainage technology (> 20 million ha of tile drained land in the Midwestern U.S.) are major reasons why the Midwestern U.S. is one of the most productive agricultural regions in the world (Fausey et al., 1995; Gilliam et al., 1999).

Corn Production

Minimizing periods of excessive soil saturation and increasing soil aeration in poorly-drained soils by artificially improving soil drainage with the installation of conventional subsurface tile drainage (FD) can improve soil workability and plant growth conditions. Subsurface tile drainage may allow for earlier planting of corn and increased plant population (Nelson and Smoot, 2012). Inducing mild drought stress early in a growing season with the presence of subsurface drainage can stimulate root development (Eghball and Maranville, 1993; Prasad et al., 2008). More robust root systems can improve plant-water use efficiency (Lorens et al., 1987; Skinner, 2008), which may account for increased plant nutrient uptake with FD compared to no subsurface drainage (ND) (Nelson et al., 2009). All of these factors may attribute for increased corn yield with FD compared to ND (Fausey et al., 1983; Kladivko et al., 2005).

Poorly-drained claypan soils have not traditionally been tile drained due to the presence of a shallow slowly permeable (K_{sat} = <0.01 µm sec^{-1}) (Watson, 1979) claypan layer that results in the need for narrow tile spacings to sufficiently increase the drainage of the soil to a level that would improve crop production (Miller et al., 1914). Therefore, cost of installing subsurface tile drainage systems in claypan soils would be relatively high. Increased land prices (University of Missouri, 2009) and relatively high grain prices currently in the region may make tile draining poorly-drained soils that have not traditionally been drained an economically viable management option to reduce excessive soil moisture and increase crop yields.

Six years of research conducted on a claypan soil in Northeast Missouri has shown increased corn yield (13-82%) with FD (6.1 m spacing) compared to ND (Nelson et al., 2009; Nelson and Smoot, 2012; Nelson and Motavalli, 2013). A unique trend from these tile drainage studies on claypan soils was that FD resulted in increased corn yield compared to ND in both wet and dry growing seasons. Cool, wet springs and dry, warm summer months typical of the central Midwest region of the U.S. in combination with early planting dates (Norwood and Currie, 1996; Kucharik, 2008; Van Roekel and Coulter, 2011), increased root development (Eghball and Maranville, 1993), and increased water use efficiency during the dry summer months (Lorens et al., 1987; Tuberosa et al., 2007; Skinner, 2008) may explain how FD increased corn yields compared to ND in relatively dry growing seasons.

Forage Production

The United States beef cattle industry has increased in value by 32% from 2002 to 2011 and is presently estimated to be worth $79 billion dollars (USDA, 2013). As livestock demand and production continue to rise, there is a greater need for increased forage production, as well as improved forage quality. Missouri is the second largest producer of cows that have calved in the United States (USDA, 2014). Forage production on moderate to poor farmland such as poorly-drained, floodplain soils may have the greatest potential for increased forage production to meet future demands without requiring an expansion of forage acres.

Subsurface tile drainage management may be one option to increase forage production on poorly-drained soils. The greatest concern with forage production in poorly-drained soils is forage growth and survival in saturated soil conditions. Extended periods of saturated soil conditions during a growing season may lower forage production by inhibiting seed germination (Benjamin, 2013), reducing plant growth (Licht and Al-Kaisi, 2005), and increasing the incidence of disease, and nutrient loss (Drury et al., 1999; Drury et al., 2006). The potential for soil compaction has been reported to increase with water content (Unger and Kaspar, 1994) and can be a major concern in forage grazing systems due to livestock and farm equipment traffic. Soil compaction has been found to reduce root growth and crop yield (Sweeney et al., 2006). Research evaluating the effect of subsurface drainage on forage production is limited. A three-year study on a claypan soil reported that the presence of subsurface tile drainage increased annual alfalfa (*Medicago sativa* L.) yield 6% compared to ND (Rausch et al., 1990). As forage prices continue to increase, the potential to improve forage quality and production in poorly-drained soils with the addition of subsurface tile drainage could become an economically viable management option.

Environmental Impact of Subsurface Drainage

Water Quality

The increased use of FD in agricultural fields has led to environmental concerns regarding nutrient (N and P) loading of surface waters (USEPA, 1992). An increased rate of water infiltration and transport out of soils with FD has increased N and in some instances P entering surface waters (Fausey et al., 1995; Gilliam et al., 1999). Aquatic ecosystems can be sensitive to anthropogenic additions of N and P that are the major contributors to environmentally degrading processes of eutrophication and hypoxia (USEPA, 1992). Concentrations of N and P in surface waters are naturally low and the most limiting nutrients in aquatic ecosystems. Anthropogenic additions of N and P in surface waters can stimulate rapid algae growth which, in turn, deplete oxygen levels below what is required for high forms of aquatic life (Burkart and James, 1999). Additionally, nitrate-N concentration above 10 mg N L^{-1} in drinking water has been reported to cause health problems (USEPA, 2009).

Nitrate entering surface waters as a result of tile drainage water is often considered of greater concern than ortho-P due to the high mobility of nitrate in soil compared to P (Sims et al., 1998; Burkart and James, 1999). Additionally, the recent shift toward continuous corn production could further increase nitrate-N loss in tile drainage water as higher annual rates of N are required to obtain maximum yield as compared to crop rotations with lower N-requiring crops such as soybean, small grains, or forage grasses (Adviento-Borbe et al., 2010). A three-year continuous corn study with N applied at 224 kg N ha^{-1} annually, reported nitrate-N loss through tile drainage water as high as 59 kg N ha^{-1} annually (Gast et al., 1978). Annual flow-weighted mean concentration of nitrate-N in tile water from fields in corn production are commonly greater than 10 mg N L^{-1} (Baker and Johnson, 1981; Randall and Vetsch, 2005) and have been reported as high as 43 mg N L^{-1} (Gast et al, 1978). However, abnormally dry conditions that limit tile flow can result in higher flow-weighted mean concentration of nitrate-N in tile water compared to what would commonly be observed (Drury et al., 1993).

Subsurface tile drainage has been shown to improve water quality in regard to P loss from agricultural fields. The greatest potential for P loading of surface waters from agricultural fields was typically through surface water runoff and soil erosion (Fausey et al., 1995; Elliott et al., 2002). The presence of subsurface tile drainage has been reported to reduce P loading through the reduction of surface water runoff and soil erosion (Zucker and Brown, 1998; Fausey et al., 1995). Over a variety of mineral soil types, annual dissolved P loss through tile drainage has been found to range from 0 to 337 g P ha^{-1} (Bolton et al., 1970; Baker, et al., 1975; Algoazany et al., 2007; Oquist et al., 2007; McDowell et al., 2008), which was likely not of environmental or agronomic significance (Sims et al., 1998).

Greenhouse Gas Emissions of Nitrous Oxide

Minimizing extended periods of soil saturation with the presence of subsurface tile drainage could reduce denitrification loss and subsequent soil N_2O emissions. Nelson et al. (2009) found that the installation of tile drainage in a poorly-drained claypan soil increased corn yields and increased plant N uptake up to 46%. The combined effect of minimizing saturated soil conditions and increased plant N uptake with subsurface tile drainage may significantly lower soil N_2O emissions. No published research at this time has evaluated the impact of FD on soil N_2O emissions compared to ND.

Managed Subsurface Drainage

Impact of Managed Subsurface Drainage on Water Quality

Research has shown that a significant portion of the annual nitrate-N loss through tile drainage water occured during the non-cropping period (Drury et al., 2009). A managed subsurface drainage system (MD) is similar to FD, except for the addition of a water level control structure, which allows for the control of tile drainage flow. By restricting tile drainage flow during the non-cropping period, MD can potentially reduce annual nitrate-N loss through tile drainage water compared to FD (Evans et al., 1995; Gilliam et al., 1999).

Although research is limited, Drury et al. (2009) reported a 32% reduction in annual nitrate-N through tile drainage water with MD compared to FD. The ability to reduce annual nitrate-N loss through tile drainage water with MD compared to FD was derived from reducing the amount of water drained during the non-cropping period (Evans et al., 1995; Fausey et al., 1995). Previous research has reported that MD reduced annual water drained 30 to 50% compared to FD (Gilliam et al., 1979; Evans et al., 1995; Drury et al., 2009). Additionally, it has been theorized that increased soil moisture during the non-cropping period with MD compared to FD could increase denitrification loss, thereby, reducing nitrate-N concentration in the tile drainage water and subsequent N loading of surface waters due to tile drainage (Gilliam et al., 1999). However, reduced nitrate-N concentration in tile drainage water with MD compared to FD has not been observed.

Agronomic Benefits of Managed Subsurface Drainage

Drought conditions resulting in plant water stress during a growing season can significantly reduce yield of forages (Rausch et al., 1990; Sheaffer et al., 1992; Skinner, 2008) and corn production systems (Duvick, 2005). The percent yield reductions associated with drought conditions are dependent on the severity, duration, and timing of water stress in relation to the plant development stage (Prasad et al., 2008). Corn is particularly sensitive to water stress during reproductive growth stages of development

(Prasad et al., 2008). Claassen and Shaw (1970) reported a 50% reduction in corn yield when plant available water was limited during silking. With the ability to restrict tile drainage flow, MD could increase the retention of crop available water and nutrients during dry periods of the growing season (Wesström and Messing, 2007) which could increase yield production compared to FD.

Research evaluating the effect of MD on crop yield compared to FD is limited. Over a five-year study in Indiana, MD increased corn yield 5.8 to 9.8% compared to FD (Delbecq et al., 2012). However, Drury et al. (2009) reported that MD increased corn yield 1 to 5% compared to FD over a two-year study. More research is needed to determine what soil environments and climatic conditions MD produce greater corn yields compared to FD.

Controlled-Release Polymer-Coated Urea Fertilizer

Introduction

Controlled-release, polymer-coated urea fertilizer (PCU) may reduce the high potential for gaseous N loss in wet soil environments through a slow release of N into the soil environment after application of N. The rate of N release from PCU is a function of moisture and temperature (Fujinuma et al., 2009). In Northeast Missouri, PCU applied in April released less than 30% urea-N into the soil as of June when broadcast on the soil surface (Nash et al., 2012a) and less than 40% when incorporated in the soil at a shallow depth (2-5 cm) (Nelson et al., 2014). Results suggest that increased soil contact with PCU through incorporation may increase the rate of urea-N release. However, the slower release of urea-N with this technology could reduce soil gaseous N loss by limiting the availability of applied N until later in the growing season when soil conditions are less conducive to volatilization or denitrification and when plant N uptake is greater.

Controlled-Release Nitrogen Fertilizer Effect on Gaseous Nitrogen Loss

Research evaluating the effect of controlled-release urea fertilizers on NH_3 volatilization loss compared to traditional, dry urea fertilizer (NCU) is limited. A study by Matocha (1976) found that slow-release, sulfur-coated urea fertilizers reduced NH_3 volatilization by 9.9 times that of NCU. However, Jantalia et al. (2012) reported a 38% increase in volatilization loss with PCU compared to NCU when broadcast applied, which may have been due to irrigation water being applied directly after N application.

No research has evaluated the effect of PCU fertilizer on denitrification loss. Numerous studies have evaluated whether PCU reduces soil N_2O emissions compared to applications of NCU (Halvorson et al., 2013; Xu et al., 2013). In irrigated corn, PCU reduced soil N_2O emissions 34 to 48% compared to NCU in Colorado (Halvorson et al., 2010a; Halvorson and Del Grosso, 2013). In a claypan soil, Nash et al. (2012b) reported a 5% increase in soil N_2O emissions with PCU compared to NCU. Increased soil N_2O emissions with PCU compared to NCU in a claypan soil may have been due to the persistence of saturated soil conditions later into the growing season which counteracted the usual reduction in soil N_2O emissions associated with a slow release of N over time.

Controlled-Release Nitrogen Fertilizer Effect on Plant Nitrogen Uptake and Yield

Reduced loss of applied N with PCU compared to NCU may increase plant N uptake and corn yield; however, the effectiveness of PCU has been found to vary due to factors, such as climate, soil type, landscape position, and N fertilizer placement. In a poorly drained claypan soil of the Midwestern U.S., PCU increased corn yield 20% and plant N uptake 24% compared to NCU in a low-lying landscape position, while similar yield and lower uptake of N with PCU compared to NCU was observed at the summit landscape position (Noellsch et al., 2009). Another study on a poorly drained claypan soil reported a 33% increase in corn yield with PCU compared to NCU when broadcast-applied at preplant, as compared to similar yields when deep-banded (Nash et al., 2013). Polymer-coated urea was not found to increase corn plant N uptake or yield compared to NCU in select studies in Minnesota, Colorado, and Ontario, Canada (Drury et al., 2011; Halvorson and Del Grosso, 2012; Halvorson and Del Grosso, 2013; Ventera et al., 2011). Contrasting corn plant N uptake and yield response with PCU compared to NCU may have been due to greater soil drainage, drier, and/or cooler conditions compared to studies on claypan soils in the Midwestern U.S.

Polymer-Coated Urea in Combination with Managed Subsurface Drainage

Combining PCU and MD may greatly reduce early season N loss and increase plant water and N uptake during the dry summer months which could further increase corn production and reduce annual nitrate-N loss through tile drainage water. Nelson and Motavalli (2013) reported PCU increased corn yield 7% compared to NCU with FD (12.2 m spacing). However, Nelson et al. (2009) found reduced corn yield (6%) with PCU compared to NCU with FD in an extremely dry year. No research has evaluated the effect of PCU on nitrate-N loss through tile drainage water flow. With a shift towards continuous corn production in the Midwestern U.S. and increasing environmental concern with water quality regarding N and subsurface tile drainage, research is needed to determine if combining PCU and MD management can increase corn production and reduce annual nitrate-N loss through tile drainage water.

Objectives

Primary Research Objective

To determine if a managed subsurface drainage and/or a controlled release polymer-coated urea fertilizer can increase corn and forage production and reduce environmental N loss in poorly-drained soils in upland or floodplain landscape positions.

Specific Research Objectives

1. To determine if the presence of tile drainage (FD or MD) in combination with a controlled-released PCU fertilizer can increase corn yields in a poorly-drained upland soil (Putnam silt loam) and bottomland soil (Wabash silty clay).
2. To determine if the presence of tile drainage (FD or MD) can increase forage biomass yields (winter rye and sorghum) in a poorly-drained, bottomland soil (Blackoar silt loam).
3. To determine whether the presence of tile drainage (FD or MD) in combination with PCU can reduce gaseous N loss compared to ND and NCU in a poorly-drained, upland soil (Putnam silt loam) in corn production.
4. To quantify the amount of annual NO_3^--N loss and the flow-weighted mean concentration of NO_3^--N in the tile water due to the soil properties, landscape position, and crop production system.
5. To determine the effectiveness of MD and PCU (corn production only) to reduce annual NO_3^--N loss through tile drainage water across soil properties, landscape position, and crop production systems.

Hypotheses

Specific Research Hypotheses

1. Poor soil aeration and a high potential for environmental N loss due to saturated soil conditions is typically the most limiting factor in corn production in the poorly-drained, Putnam and Wabash soils. Installation of tile drainage in combination with PCU should minimize the occurrence of saturated soil conditions, increase soil aeration, reduce environmental N loss and subsequently increase corn yields.
2. Forage production on poorly-drained, bottomlands soil is often limited due to saturated soil conditions and subsequent poor soil aeration. The presence of tile drainage should minimize the occurrence of saturated soil conditions, increase soil aeration, and subsequently increase forage biomass yields.
3. The presence of tile drainage should reduce the periods of saturated soil conditions, improving root development and subsequently increasing corn N uptake. While, the controlled-released properties of PCU should minimize environmental N loss prior to significant corn N uptake compared to NCU. The combination of tile drainage (FD or MD) with PCU should minimize gaseous N loss compared to the application of NCU with MD in a poorly-drained, upland soil (Putnam soil) in corn production.
4. Annual NO_3^--N loss and flow-weighted mean concentration of NO_3^--N in the tile drainage water from corn production on the upland and bottomland soils should be similar to what has been reported in previous research on corn production in upland soils. Annual NO_3^--N loss and flow-weighted mean concentration of NO_3^--

N in the tile drainage water with forage production on a bottomland soil should be lower than what is commonly reported with corn production systems due to reduce N fertilizer inputs and the potential for plant N uptake year-round.

5. Managed drainage should reduce annual NO_3^--N through the tile drainage water compared to FD by reducing tile drainage flow during periods of time when drainage is not advantageous to crop production. The magnitude of NO_3^--N reduction could vary due to the soil properties, landscape position, and cropping production system, as a result in differences in tile drainage flow. Application of PCU in a corn production system with MD could further reduce annual NO_3^--N loss through the tile drainage water by minimizing the amount of N available for leaching into the tile drain during the spring period when flow is not restricted with MD, as compared to an NCU application.

Arrangement of Dissertation

This dissertation contains seven chapters which have been organized in a standard research journal format. Chapters 2 through 4 provide the results on corn production, nitrate-N loss through tile drainage water, and soil N_2O and NH_3 gaseous emissions due to the subsurface drainage system and N fertilizer source in a poorly-drained claypan soil. Chapters 5 and 6 provide the results on corn production and nitrate-N loss through tile drainage water due to the subsurface tile drainage systems and N fertilizer source in a poorly-drained floodplain soil. Chapters 7 and 8 provide the results on forage production and nitrate-N loss through tile drainage water due to the subsurface tile drainage systems in a poorly-drained floodplain soil. A final concluding chapter is added to provide a synthesis of the dissertation research.

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CHAPTER 2

CORN YIELD RESPONSE TO MANAGED DRAINAGE AND POLYMER-COATED UREA FERTILIZER IN A POORLY-DRAINED, CLAYPAN SOIL

ABSTRACT

With poorly-drained claypan soils in the Midwestern U.S., it is common to have wet soil conditions in the spring and dry soil conditions in the summer. Management practices that can improve or mitigate the effects of excessive wet and dry soil conditions are essential to obtain maximum corn (*Zea mays* L.) yield potential. The objectives of the four-year study was to determine if subsurface drainage [free drainage (FD) or managed drainage (MD)] with polymer-coated urea (PCU) can increase corn yield compared to application of non-coated urea (NCU) without drainage (ND) in a claypan soil. Corn grain yields were low over the four-year study due to extreme wet conditions in 2010 that delayed planting, and mild to extremely summer drought conditions in 2011-2013. Averaged over 2010-2013, corn grain yields ranged from 4.76 to 5.75 Mg ha^{-1}. Averaged over 2010-2013, the presence of drainage (FD or MD) increased corn yield (15-21%) compared to ND when NCU was applied. In absence of drainage, PCU increased corn grain yields 20% compared to NCU, which indicated that PCU mitigated the high N loss potential in a wet soil environment. Managed drainage averaged a 4% increase in corn yield compared to FD. Corn yield increase with drainage compared to ND were limited over the four years of this research; however, greater corn yield benefits from drainage of claypan soils might occur in years with greater overall yield potential.

INTRODUCTION

Poor internal drainage of claypan soils in the central Midwest U.S. can lead to a variety of corn production issues, such as high N loss and trafficability issues related to saturated soil conditions. Claypan soils are characterized by having a subsurface soil horizon that has 100% greater clay content than the horizon above it and slow permeability (Jung et al., 2006; Myers et al., 2007). Leaching of water through the claypan layer is minimal (Ksat <0.01 μm sec^{-1}) (Watson, 1979) and results in a perched water table when rainfall exceeds the rate of evapotranspiration, as is common during the spring and fall months in the region (Yeh et al., 1998). Management practices that reduce the occurrence of saturated soil conditions or mitigate its possible deleterious effects on plant growth are essential to obtaining the maximum corn yield potential.

Controlled release, polymer-coated urea fertilizer (PCU) may reduce the high potential for N loss in wet soil environments through the slow release of N into the soil environment. The rate of N release from PCU is a function of moisture and temperature (Fujinuma et al., 2009). In the central U.S., it was reported that PCU applied in April retained up to 60% of applied N in the polymer-coating through May (Nash et al., 2012; Nelson et al., 2014). Limiting the availability of applied N for an extended period of time after application may reduce early season N loss and increase plant N uptake (Nelson et al., 2008).

The effectiveness of PCU to increase plant N uptake and corn yield compared to non-coated urea (NCU) may vary due to factors, such as climate, soil type, landscape position, and N fertilizer placement. In a claypan soil of the Midwestern U.S., PCU increased corn yield (20%) and plant N uptake (24%) compared to NCU in a low-lying landscape position, while similar yield and lower uptake of N with PCU compared to NCU were observed at the summit landscape position (Noellsch et al., 2009). Another study on a claypan soil reported a 33% increase in corn yield with PCU compared to NCU when broadcast-applied at preplant, as compared to similar yields when deep-banded (Nash et al., 2013). Polymer-coated urea was not found to increase corn plant N uptake or yield compared to NCU in select studies that took place in Minnesota, Colorado, and Ontario, Canada (Drury et al., 2011; Halvorson and Del Grosso, 2012; Halvorson and Del Grosso, 2013; Ventera et al., 2011). Contrasting corn plant N uptake and yield response with PCU compared to NCU may have been due to greater soil drainage, drier, and/or cooler conditions compared to studies on claypan soils in the Midwestern U.S.

Subsurface tile drains (FD) are commonly used in poorly-drained soils to increase soil drainage and minimize periods of extended soil saturation which may increase corn yield. Increased corn yield with the presence of subsurface drainage was likely caused by increased plant population (Nelson and Smoot, 2012), and improved plant growth conditions as a result of increased root development (Eghball and Maranville, 1993), plant-water efficiency (Lorens et al., 1987; Skinner, 2008), and plant nutrient uptake (Nelson et al., 2009). Additionally, corn yield generally increases with earlier planting dates in the Midwestern U.S. (Kucharik, 2008); therefore, minimizing saturated soil conditions in the spring with FD may allow for earlier planting of corn and a subsequent increase in corn yields.

Poorly-drained claypan soils have not traditionally been tile drained due to the presence of a shallow impervious claypan layer that results in the need for narrow tile spacings in order to effectively enhance the drainage of the soil. Therefore, costs for installing subsurface tile drainage systems in the claypan region are relatively high. Increased land prices in the region (University of Missouri, 2009) and relatively high grain prices may now make subsurface drainage a viable management option to reduce excessive soil moisture conditions commonly experienced in the spring. Initial research on claypan soils have reported up to an 82% increase in corn yields with FD compared to ND (Nelson et al., 2009; Nelson and Smoot, 2012; Nelson and Motavalli, 2013). Research on poorly-drained Clermont soils that are non-traditionally tile drained reported a 7% increase in corn yields with the presence of subsurface drainage compared to no drainage (ND) (Fausey et al., 1983; Kladivko et al., 2005).

Wet soil conditions in the spring in combination with drought conditions during the summer months have resulted in relatively lower corn production in the region. Corn production may greatly benefit from the addition of a water level control structure with subsurface drainage systems, which are referred to as managed subsurface drainage systems (MD). Managed drainage systems have the same soil drainage capabilities as FD, but have the added ability to increase the retention of crop available water and nutrients during the dry summer months through the added ability to manage the flow of water through the drainage tiles (Wesström and Messing, 2007). Over a five year study in Indiana, MD increased corn yield (5.8-9.8%) compared to FD (Delbecq et al., 2012). Drury et al. (2009) reported that MD increased corn yield (1-5%) compared to FD over a two year study. More research is currently needed to determine if MD can consistently produce greater corn compared to FD.

Increased use of subsurface drainage in the Midwest U.S. has been linked to increased N pollution of surface waters (USEPA, 1992). Tile drained fields in corn production are thought to be a major contributor to this pollution due to high N inputs required to obtain maximum corn yields (Adviento-Borbe et al., 2010). Combining a controlled-release N fertilizer with MD may negate the increased potential for nutrient leaching in claypan soils, while maintaining soil moisture conditions at or near optimal levels required to obtain maximum corn yield potentials. The objective of the study was to determine if MD with PCU could increase corn yield in a claypan soil located in the Midwestern U.S.

MATERIALS AND METHODS

Site Description and Experimental Design

A four-year study with continuous corn was initiated in 2010 at the University of Missouri's Greenley Memorial Research Center, located in Northeast Missouri (40^{o}1'17" N, 92^{o}11'24.9" W). Subsurface tile drains and water level control structures (Agri Drain Corporation, Adair, IA) were installed at the site in August 2009, at a depth of 0.6 m with 6.1 m spacings (Fig. 2.1). Plot sizes were 9.1 by 61 m (replication 1) and 91 m (replication 2). A plastic lining was buried in the soil approximately 0.7 m deep and surface berms separated plots in order to restrict movement of water and N into adjacent plots.

Treatments were arranged in a two factor, randomized complete block design with two replications. One factor was drainage (FD, MD, and ND) and the other factor was nitrogen fertilizer sources [NCU and PCU (ESN, Agrium Advanced Technology, Denver, CO)], which were preplant, broadcast applied at 202 kg N ha^{-1} and immediately incorporated into the soil (5-10 cm) using a cultivator. A non-fertilized (NFC), ND control plot was included in each replication. Tillage occurred in the fall and spring with a Tilloll, (Landoll Corp., Marysville, KS), while vertical tillage (Case IH 330, Racine, WI) was used in 2012 as an additional method of residue management. Crop protection and production management including plant dates, harvest dates, and water level control with MD can be found in Table 2.1 and Figure 2.2.

Corn was planted (John Deere 7000, Moline, IL) in 76-cm rows at 74,100 seeds ha^{-1}. Corn hybrid 'DeKalb 62-64 VT3' was planted in 2010-2012, and 'DeKalb 62-97 RIB' was planted in 2013. Corn grain yields (adjusted to 150 g kg^{-1} moisture) were obtained from harvesting (Wintersteiger Delta 1650, Austria) the center eight corn rows that spanned the 6.1 m spacing of the tile drains in the plots with tile drainage.

Corn grain samples were collected annually from each plot during harvest were analyzed for protein, moisture, starch, and oil concentration with a Foss Infratec 1241 (Eden Prairie, MN). Annual collection of whole corn plant samples at physiological maturity were taken directly over a tile drain (1.5 m) and between the tile drains (1.5 m) in each plot and were weighed, ground, dried, and used to estimate silage yield. Whole corn plant samples were then analyzed for total N concentration by combustion using a total C:N analyzer (LECO, TruSPEC CN Analyzer, St. Joseph, MI).

The soil series at the field site was a Putnam silt loam (fine, smectitic, mesic Vertic Albaqualfs), which contained a claypan subsoil layer at a depth of approximately 0.61 m. Soil samples were collected from each plot to a depth of 0.3 m in the fall after harvest in each year using a Giddings probe (Giddings Machine Company, Windsor, CO). Soil properties presented by year in Table 2.2 were analyzed using standard soil testing analytical procedures for Missouri (Nathan et al., 2006). Soil NH_4^+-N and NO_3^-N concentrations were converted from mg kg^{-1} to kg ha^{-1} based on soil bulk density measurements taken at the depths of 0-0.3, 0.3-0.6, and 0.6-0.9 m at the field site in 2013. Rainfall data were collected on-site during the study using an automated weather station (Campbell Scientific, Inc., Logan, UT) (Fig. 2.2). Rainfall and air temperature data from the ten years prior to the initiation of the study (2000-2009) were collected at the field site (Fig. 2.3).

Statistical Analysis

Analysis of variance (ANOVA) using the statistical program SAS v9.3, with PROC GLM was used to analyze the interaction and main effects of drainage and N fertilizer source on corn production measurements (SAS Institute, 2013). Results from the overall ANOVA analyses including year are presented in Table 2.3. The NFC/ND control was included in the analysis of corn grain yields. Fisher's Protected LSD at P = 0.05 or 0.10 was used to separate means and determine significant treatment effects.

RESULTS AND DISCUSSION

Rainfall

In the ten years prior (2000-2009) to the study (2010-2013), the average rainfall from March through November at the Greenley Research Center was 863 mm (Fig. 2.3). In combination with decreased air temperature and low evapotranspiration rates, high rainfall during April through June often results in saturated soil conditions. Rainfall typically decreases during the summer months, which coincides with peak air temperature and plant water demand. This pattern has been commonly observed in the Midwestern U.S. and can result in low corn production in poorly-drained, claypan soils unless best management practices are used to counteract the naturally saturated and dry soil conditions observed during the spring and summer months, respectively.

Total rainfall from March through November was 1191, 788, 603, and 880 mm in 2010, 2011, 2012, and 2013, respectively (Fig. 2.2). The 2010 growing season was exceptionally wet throughout the entire growing season and planting was delayed until 25 June. In 2011-2013, rainfall distribution was similar to the historical rainfall distribution. However, 2012 and 2013 had extreme drought conditions during the summer months limited the potential for increased corn grain yields with the presence of drainage. Annual N application of 202 kg N ha^{-1} in combination with dry conditions over the summer months of 2011 through 2013 presumably limited plant N uptake and environmental N loss that resulted in an accumulation of residual soil N over the four-year study (Table 2.2).

Corn Grain Yields

Corn grain yields were significantly ($P \leq 0.0001$) affected by the interaction of drainage and N fertilizer source (Table 2.3). Corn grain yield potential was low over the four years due to extreme wet conditions delaying planting in 2010 until 25 June and mild to extreme summer drought conditions in 2011-2013. Averaged over 2010-2013, corn grain yields ranged from 4.76 to 5.75 Mg ha^{-1} (Fig. 2.4). Although three of the four years could be classified as dry years, wet soil conditions in the spring resulted in a high potential for early season N loss. Even with accumulation of residual soil N over the four-year study PCU increased corn grain yield 20% compared to NCU in absence of drainage. This indicated that N loss through denitrification was probably high in absence of drainage due to saturated soil conditions in the spring. These results parallel two other studies on claypan soils which reported increased corn yields (3-20%) with PCU compared to NCU in absence of drainage (Nelson et al., 2009; Noellsch et al, 2009; Nelson and Motavalli, 2013). Studies on soils with greater internal drainage, drier conditions, and/or cooler climates reported similar to reduced corn yields with PCU compared to NCU (Drury et al., 2011; Halvorson and Del Grosso, 2012; Halvorson and Del Grosso, 2013; Ventera et al., 2011). These results indicate the potential to increase corn yield with PCU compared to NCU were greater in soil environments with high N loss potential due to saturated soil conditions. Corn grain yields with the presence of drainage (FD or MD) regardless of N fertilizer source (PCU or NCU) were similar to the corn yield with PCU in absence of drainage. Limited corn grain yield increase was observed in the study with FD or MD compared to ND. This was likely due to the low overall corn grain yield potential from 2010-2013. However, the presence of drainage likely reduced the potential for early season N loss since corn grain yields increased 15-21% with drainage (FD and MD) when NCU was applied. Averaged over N fertilizer source, corn yield was 5.75 Mg ha^{-1} with MD and 5.55 Mg ha^{-1} with FD. Drury et al. (2009) reported a similar corn yield increase with MD compared to FD over a two-year study which was presumably due to the added ability to conserve of soil water during the dry periods with MD.

Grain Protein and Whole Plant N Concentration

The main effect of N fertilizer source significantly ($P \leq 0.03$) affected corn grain protein concentration (Table 2.3). Corn grain protein increased 3% from 86.5 g kg^{-1} with NCU to 89.4 g $kg^{-1}$with PCU (Table 2.4). Nelson et al. (2014) reported a 5 to 10% increase in corn grain protein with PCU compared to NCU in a non-drained claypan soil.

This response may indicate that the corn grain protein response between PCU and NCU increased with wetter soil conditions. Dry summer conditions observed in three of the four study years may have reduced some of PCUs' ability to increase corn grain protein concentration compared to NCU.

The main effect of N fertilizer source significantly ($P \leq 0.08$) affected whole corn plant N concentration at physiological maturity (Table 2.3). Whole corn plant N concentration increased 9% from 8.38 g kg^{-1} with NCU to 9.17 g kg^{-1} with PCU (Table 2.4). Although residual soil N was high in two of the four study years, this result indicated that PCU increased plant N uptake (data not presented, $P = 0.2065$) compared to NCU. That finding paralleled previous research with PCU on a claypan soil that reported a 24% increase in plant N uptake with PCU compared to NCU. However, Nelson et al. (2009) reported reduced plant N uptake with PCU compared to NCU on a claypan soil in a year that had an abnormally low amount of rainfall during the spring. Rainfall during the spring in 2010-2013 was similar to greater than the ten year average (Fig. 2.3) and likely led to a high potential for N loss. Therefore, increased whole corn plant N concentration with PCU compared to NCU observed during the study was presumably due to reduced early season N loss derived from the controlled release properties of PCU.

Whole plant N concentration was significantly ($P \leq 0.08$) affected by the main effect of drainage which interacted with year (Table 2.3). There were no differences in whole plant N concentration among drainage treatments in 2011 and 2012 (Table 2.5). In 2013, both FD (10.12 g kg^{-1}) and MD (10.52 g kg^{-1}) increased whole plant N concentration compared to ND (7.77 g kg^{-1}). Nelson et al. (2009) observed a similar response in a dry year in which FD increased corn plant N uptake 11% compared to ND (Nelson et al., 2009). Greater whole plant N concentration with drainage (FD or MD) compared to ND may have been due to reduced N loss early in the growing season. Additionally, inducing mild water stress with drainage in a wet spring period may lead to increased root system development (Eghball and Maranville, 1993). Increased root system development with drainage (FD or MD) may allow for greater plant-water use efficiency (Lorens et al., 1987; Skinner, 2008) and subsequent plant N uptake during the dry summer months as compared to ND.

CONCLUSIONS

There were low overall corn grain yields during the four years of this research due to excessive rainfall in 2010 that delayed planting until June 25, and mild to extreme drought conditions in the summer months of 2011-2013. Low corn yield potential likely limited the potential for increased corn yields with the presence of drainage (FD or MD) compared to ND. However, wet soil conditions present in the spring likely led to a high potential for early season N loss. Application of PCU or the presence of drainage possibly reduced early season N loss, which resulted in the greatest corn grain yields. The occurrence of increased whole plant N concentration with PCU compared to NCU or drainage (FD or MD) compared to ND further indicated that these management practices may reduce early season N loss. Additionally, inducing mild soil water stress early in a growing season with the presence of drainage (FD or MD) may have enhanced root system development that increased plant-water use efficiency and subsequent plant N uptake during the dry summer months compared to ND. Slightly greater corn yield production with MD compared to FD was probably due to the conservation of soil water during the dry summer months. Limited corn yield increases with drainage compared to ND were observed over the four-year study on a claypan soil; however; we would expect greater corn yields from drainage in years with greater overall yield potential.

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Table 2.1. Crop protection management practices that were used over the four-year study.

Crop protection management[†]	2010	2011	2012	2013
Preplant application	---------	11 Apr. 2011	---------	---------
Glyphosate		1.06 kg ai ha^{-1}		
2,4-D		0.35 kg ae ha^{-1}		
Early post emergence application	30 July 2010	---------	11 May 2012	22 May 2013
Glyphosate	1.54 kg ai ha^{-1}		1.54 kg ai ha^{-1}	0.41 kg ai ha^{-1}
Acetochlor			1.05 kg ai ha^{-1}	1.05 kg ai ha^{-1}
Flumetsulam			0.03 kg ai ha^{-1}	0.03 kg ai ha^{-1}
Clopyralid			0.11 kg ai ha^{-1}	0.11 kg ai ha^{-1}
Non-ionic surfactant				0.25% vol./vol.
Crop oil concentrate	2.34 L ha^{-1}			
Diammonium sulfate	20.40 g L^{-1}			
UAN				2.34 L ha^{-1}
Late post emergence application	---------	8 June 2011	4 June 2012	27 June 2013
Glyphosate		1.54 kg ae ha^{-1}	0.41 kg ai ha^{-1}	0.41 kg ai ha^{-1}
Mesotrione			0.11 kg ai ha^{-1}	0.11 kg ai ha^{-1}
S-metolachlor		5.35 kg ai ha^{-1}		
Crop oil concentrate			2.34 L ha^{-1}	
Diammonium sulfate			20.40 g L^{-1}	20.40 g L^{-1}
Non-ionic surfactant				0.25% vol./vol.

[†] Herbicide chemical names: 2,4-D (2,4-Dichlorophenoxyacetic acid); acetochlor (2-chloro-2’-methyl-6’-ethyl-N-ethoxymethylacetanilide); clopyralid (3,6-dichloro-2-pyridinecarboxylic acid, monoethanolamine salt); flumetsulam (N-(2,6-difluorophenyl)-5-methyl-1,2,4-triazolo-[1,5a]-pyrimidine-2-sulfonamide); glyphosate (N-(phosphonomethyl)glycine); mesotrione (2-[4-(Methylsulfonyl)-2-nitrobenzoyl]cyclohexane-1,3-dione); *S*-metolachlor (acetamide, 2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl).

Table 2.2. Selected soil chemical properties from fall soil sampling at a depth of 0 to 0.3 m in 2010, 2011, 2012, and 2013. Data were averaged over tile drainage systems and N fertilizer source treatments.

Soil property[†]	Units	Year[§] 2010		2011		2012		2013	
pH_S (0.01 M $CaCl_2$)	------------	5.6	+/- 0.4[‡]	6.4	+/- 0.3	6.1	+/- 0.4	5.7	+/- 0.5
N.A.	$cmol_c\ kg^{-1}$	1.8	+/- 0.7	1.0	+/- 0.7	1.7	+/- 0.8	2.7	+/- 1.8
O.M.	$g\ kg^{-1}$	23	+/- 4	28	+/- 9	22	+/- 6	24	+/- 7
Bray I P	$kg\ ha^{-1}$	88	+/- 29	77	+/- 39	91	+/- 39	71	+/- 34
Exch. Ca	$kg\ ha^{-1}$	6371	+/- 1219	5636	+/- 1222	5152	+/- 1653	5110	+/- 1320
Exch. Mg	$kg\ ha^{-1}$	635	+/- 159	585	+/- 183	574	+/- 199	569	+/- 194
Exch. K	$kg\ ha^{-1}$	519	+/- 153	523	+/- 166	461	+/- 159	416	+/- 169
CEC	$cmol_c\ kg^{-1}$	19	+/- 3	16	+/- 3	16	+/- 4	17	+/- 3
NO_3^--N	$kg\ N\ ha^{-1}$	21.2	+/- 6.8	10.1	+/- 7.5	98.5	+/- 70.4	82.4	+/- 51.6
NH_4^+-N	$kg\ N\ ha^{-1}$	12.8	+/- 1.1	24.6	+/- 3.7	15.6	+/- 6.7	24.5	+/- 7.2

[†] Abbreviations: CEC = cation exchange capacity; Exch. = exchangeable; N.A. = neutralizable acidity; O.M. = organic matter.

[‡] Numbers following mean values represents plus or minus one standard deviation.

[§] Soil samples were averaged over every fertilized plot (n = 12).

Table 2.3. ANOVA table summary of corn grain yield, protein, starch, oil, whole plant N concentration, and silage yield at physiological maturity from 2010-2013.

	Corn grain				Whole corn plant[‡]	
	Yield[†]	Protein	Starch	Oil	N concentration	Silage
Source	*P* > *F*	*P* > *F*	*P* > *F*	*P* > *F*	*P* > *F*	*P* > *F*
Rep	0.0531	0.1921	0.1559	0.1177	0.9197	0.8052
Year	<.0001	<.0001	<.0001	<.0001	0.0002	<.0001
N source	0.1404	0.0120	0.3259	0.4476	0.0837	0.5031
Drainage	0.1975	0.1740	0.7153	0.1177	0.3834	0.4130
Year x N source	0.4098	0.0300	0.5200	0.2481	0.4022	0.8379
Year x Drainage	0.7457	0.1378	0.6104	0.6536	0.0820	0.6235
N source x Drainage	<.0001	0.4054	0.7404	0.6336	0.6764	0.5081
Year x N source x Drainage	0.2246	0.6082	0.6693	0.5432	0.8051	0.1538

[†] The non-fertilized, non-drained controls were included in the analysis of the interactions including drainage and N fertilizer source for corn yield only.

[‡] Whole plant analysis of N concentration and silage was evaluated over 2011-2013.

Table 2.4. Nitrogen fertilizer source main effect on corn grain protein concentration and whole plant N concentration at physiological maturity. Data were averaged over 2010-2013.

N source[†]	Grain protein[‡]	Whole plant N concentration
	--- $g\ kg^{-1}$ ----	---- $g\ kg^{-1}$ ----
PCU	89.4a	9.17a
NCU	86.5b	8.38b
LSD (P value)	0.05	0.10

[†] Abbreviations: conc. = concentration; LSD = least significant difference; NCU = non-coated urea; PCU = polymer-coated urea.

[‡] Letters following corn grain protein and whole corn plant N concentration for the main effect of N fertilizer source signify significant mean differences.

Table 2.5. Main effect of drainage on whole corn plant N concentration at physiological maturity in 2011-2013. Data were averaged over N source.

	Whole corn plant N concentration[‡]		
Drainage	2011	2012	2013
	-------------- $g\ kg^{-1}$ --------------		
ND	7.08	10.18	7.77
FD	6.97	9.76	10.12
MD	7.35	9.22	10.52
LSD $_{(0.10)}$	0.90	1.83	2.15

[†] Abbreviations: FD = free drainage; LSD = least significant difference; MD = managed drainage; ND = no drainage.

[‡] Whole corn plant samples were not collected or analyzed for N concentration in 2010.

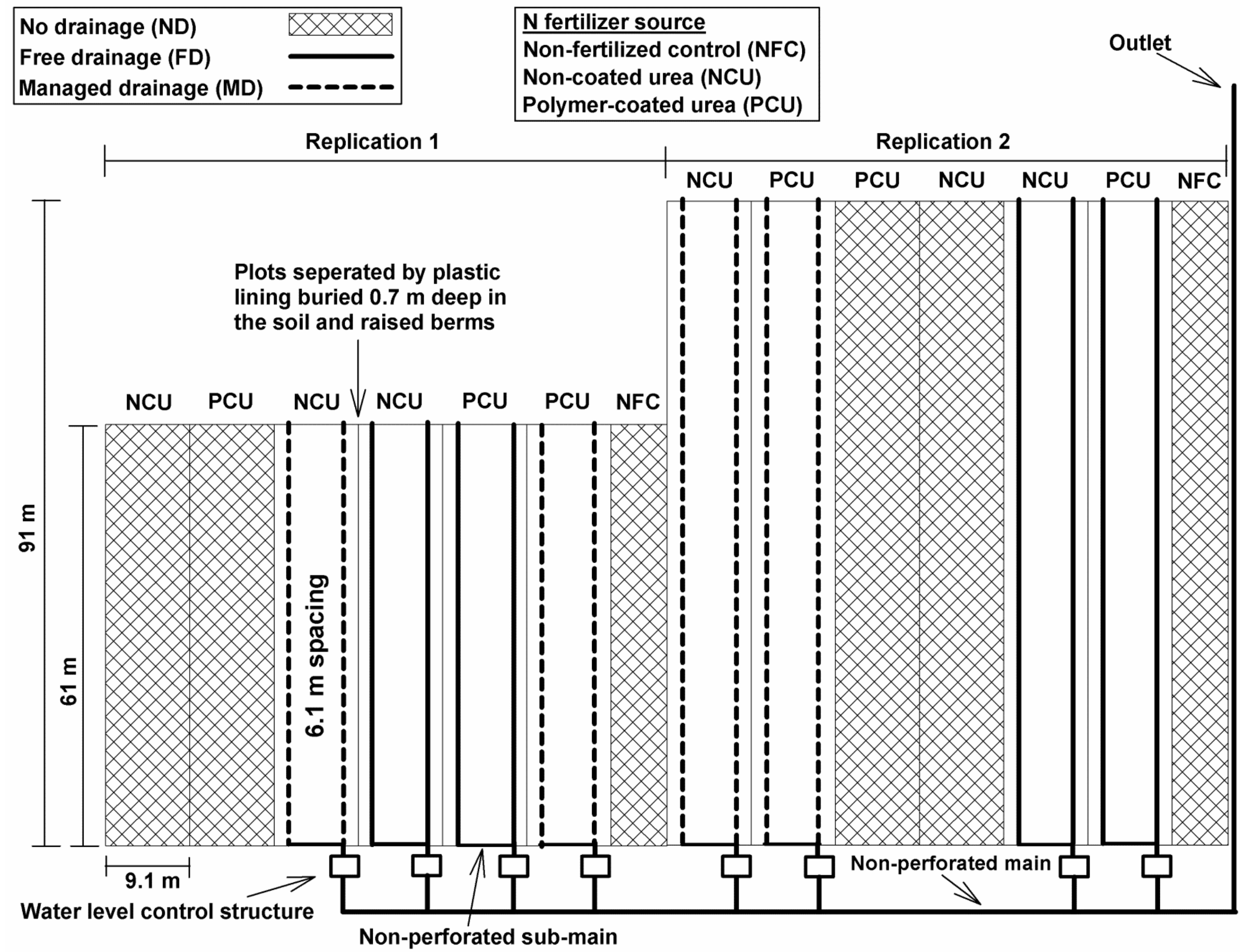

Figure 2.1. Field site layout and plot treatments including the subsurface drainage system design.

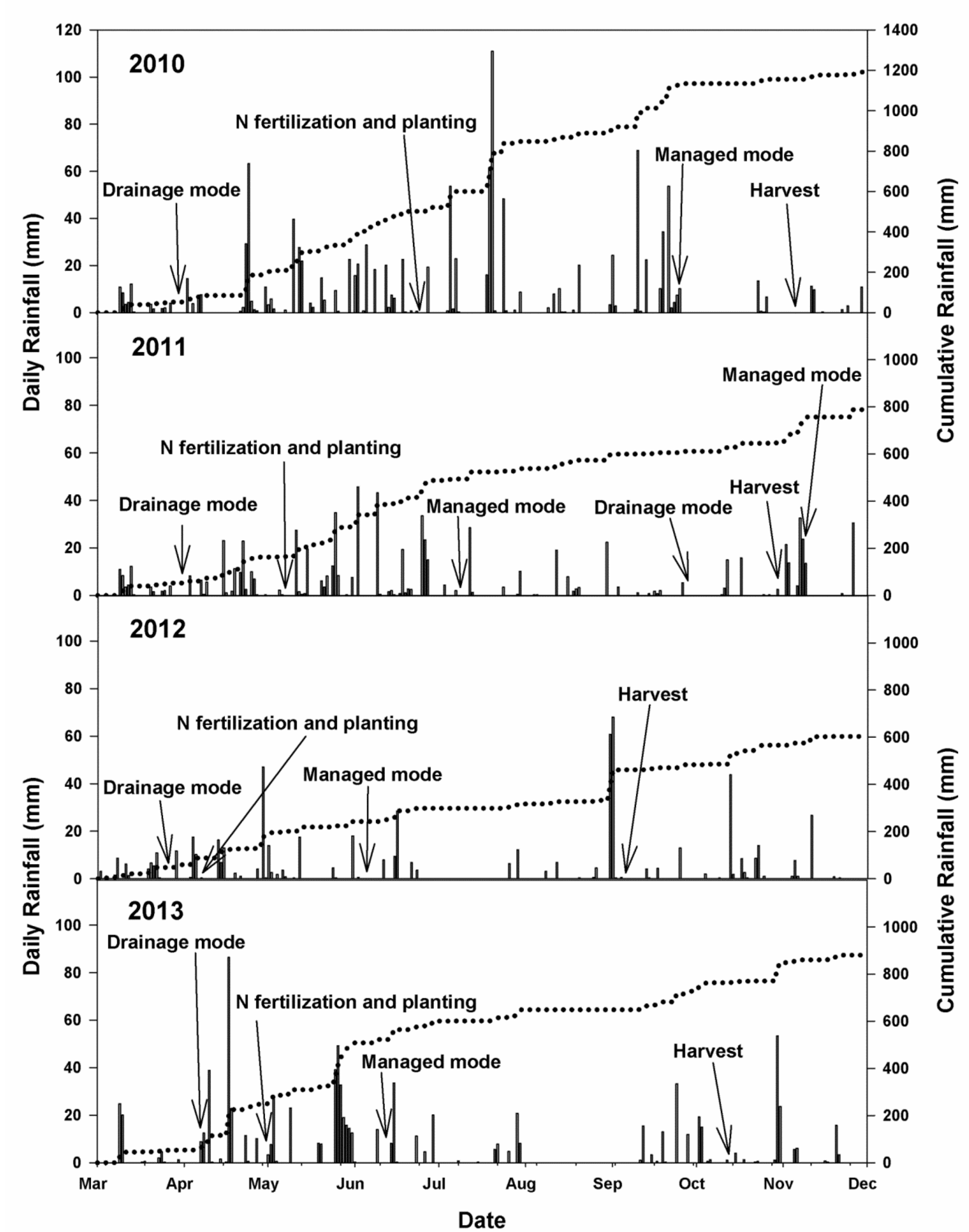

Figure 2.2. Daily (bars) and cumulative (dashed lines) rainfall from March through November at the study site from 2010-2013. Arrows indicate the dates of N fertilization, planting, harvesting, and managing of tile outflow with managed drainage.

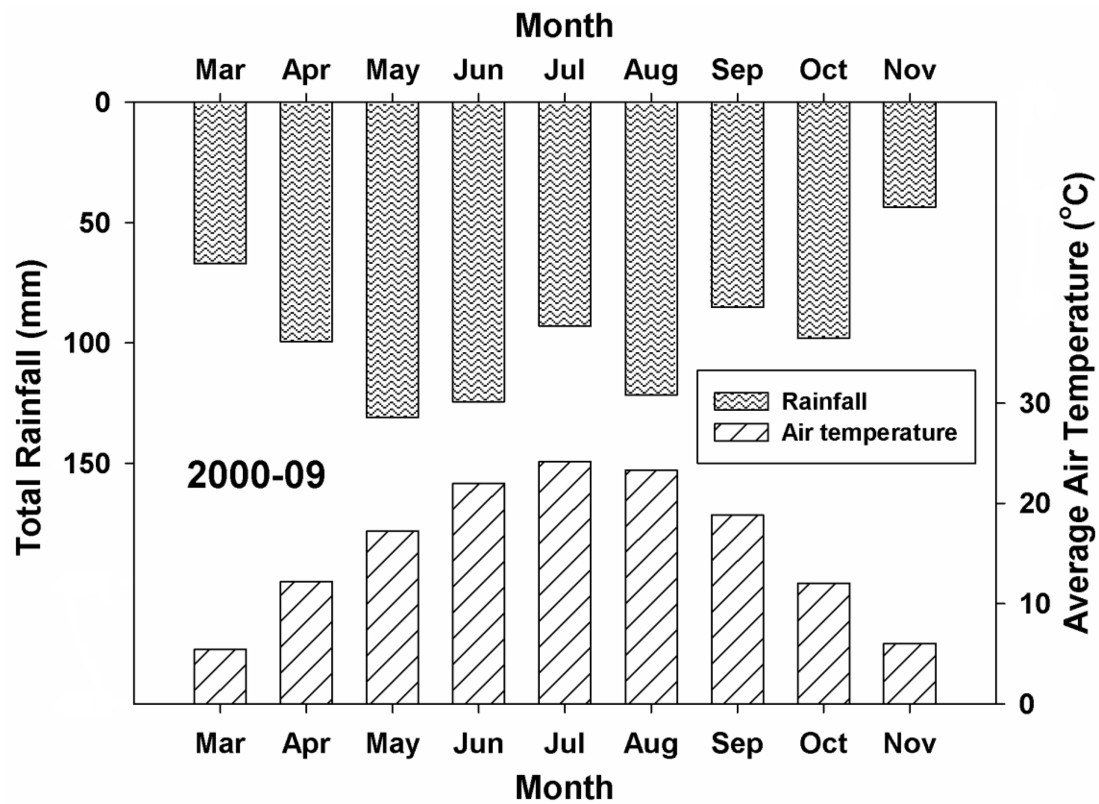

Figure 2.3. Ten year average air temperature and rainfall received at the field site by month prior to the 2010-2013 study.

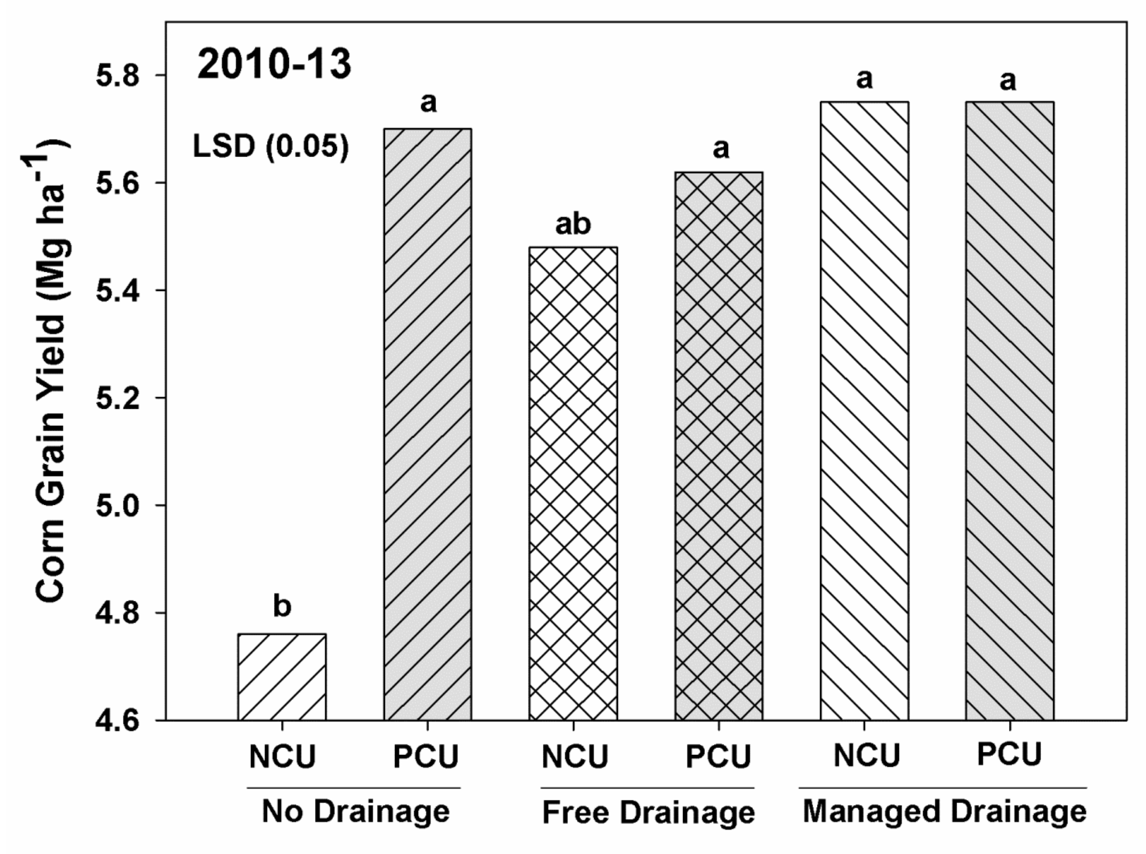

Figure 2.4. Subsurface drainage and N fertilizer source effect on corn grain yields averaged over 2010-2013. Letters above the bars represent significant differences between means among drainage and N source treatments. Abbreviations: LSD = least significant difference; NCU = non-coated urea; PCU = polymer-coated urea.

CHAPTER 3

REDUCING NITROGEN LOSS IN TILE DRAINAGE WATER WITH MANAGED DRAINAGE AND POLYMER-COATED UREA IN A CLAYPAN SOIL

ABSTRACT

Potential for NO_3^--N loss through tile drainage water in claypan soils in continuous corn (*Zea mays*. L.) production during dry years could be increased when high N fertilizer rates are applied and due to the presence of the claypan layer that restricts N leaching below the tile drains. The objective of this four-year study was to determine whether use of managed subsurface drainage (MD) in combination with a controlled-release N fertilizer could reduce the annual amount of NO_3^- loss through tile drainage water compared to free subsurface tile drainage (FD) with a non-coated urea application. Due to dry conditions over the summer and fall months, MD reduced the annual amount of water drained by at least 73% compared to FD in two of the four crop years. Low N loss and reduced corn N uptake possibly resulted in carry-over N and high soil N concentrations throughout the study, which may have limited the effect of N fertilizer source on annual NO_3^--N loss in the tile drainage water. Use of managed drainage reduced annual NO_3^--N loss in the tile drainage water by 78 to 85% in two of the years. High NO_3^--N loss reduction with MD compared to FD was largely due to dry growing season conditions in combination with wet conditions over the non-cropping period.

INTRODUCTION

Subsurface tile drainage has been shown to improve soil drainage which minimizes production issues associated with poorly-drained soils (Evans and Fausey, 1999), resulting in increased corn yields (Kladadivo et al., 2005; Nelson et al., 2009; Nelson and Smoot, 2012; Nelson and Motavalli, 2013). Tile drainage is a common practice in the Midwestern U.S. and is a major reason why it is one of the most productive agricultural regions in the world (Gilliam et al., 1999). However, the presence of tile drainage has facilitated leaching of nutrients out of soils into surface waters which has health and environmental implications (Fausey et al., 1995).

Nitrate (NO_3^-) leaching with agricultural tile drainage into surface waters is typically of great environmental concern due to the limited retention of NO_3^- in soil (Burkart and James, 1999). The recent shift toward continuous corn production could have a large impact on N loss through tile drainage as high rates of N are required to obtain high yields (Adviento-Borbe et al., 2010). A three-year continuous corn study with an annual N rate of 224 kg N ha^{-1} reported annual NO_3^--N loss through tile drainage water as high as 59 kg N ha^{-1} (Gast et al., 1978). High N loss in tile water can have a negative impact on the environment in regard to hypoxia and eutrophication (USEPA, 1992). Nitrogen is a limiting nutrient in aquatic systems and anthropogenic additions stimulated rapid algae growth which in turn depleted oxygen levels below what were required for high forms of aquatic life (Burkart and James, 1999). Additionally, a concentration of NO_3^--N above 10 mg N L^{-1} in drinking water can result in adverse health problems (USEPA, 2009). Annual flow-weighted mean concentrations of NO_3^--N in tile water from corn production fields were commonly greater than 10 mg N L^{-1} (Baker and Johnson, 1981; Randall and Vetsch, 2005) and have been reported as high as 43 mg N L^{-1} (Gast et al, 1978). However, abnormally dry conditions that limited tile flow resulted in higher flow-weighted mean concentration of NO_3^--N in tile water, as compared to a year with greater tile drainage flow (Drury et al., 1993).

Increased pressure to reduce NO_3^- loss in tile water due to environmental and health concerns has been mounting (USEPA, 1992). Managed subsurface drainage systems (MD) may be able to minimize NO_3^- loss in tile water compared to FD (Gilliam et al., 1999). Although research is limited, Drury et al. (2009) reported a 32% reduction in annual NO_3^--N in tile drainage water with MD compared to FD, while producing 4% greater corn grain yields. The ability to reduce annual N loss in tile drainage water with MD compared to FD was derived from reducing the amount of water drained during the non-cropping period with MD (Evans et al., 1995; Fausey et al., 1995). Previous research has reported that MD reduced the annual amount of water drained by 30 to 50% compared to FD (Gilliam et al., 1979; Evans et al., 1995; Drury et al., 2009). Additionally, it has been theorized that increased soil moisture during the non-cropping period with MD compared to FD could increase denitrification loss and subsequent annual N loss through tile drainage water (Gilliam et al., 1999)

Polymer-coated urea fertilizers (PCU) are controlled release fertilizers that release N into the soil environment over time after application at a rate positively correlated with moisture and temperature (Fujinuma et al., 2009). Applications of PCU in April have been reported to retain up to 60% of the applied N within the polymer-coated prill as of June (Nash et al., 2012a; Nelson et al., 2014). In a claypan soil, PCU has been found to reduce early season gaseous N loss compared to NCU (Chapter 4), presumably due to the release of urea-N into the soil environment over time compared to 100% availability in the soil directly after application with NCU. In low-lying landscape positions that are prone to wet soil conditions, Noellsch et al. (2009) reported a 24% increase in corn N uptake and 48% N recovery efficiency which was probably due to reduced N loss. The combination of MD with PCU could have a synergistic effect on reducing annual N loss in tile drainage water. No research has currently evaluated the impact of MD and PCU on N loss in tile drainage water.

Claypan soils are classified as having a subsurface soil horizon as shallow as 0.6 m depth that are high in clay content and have a low permeability (Jung et al., 2006; Myers et al., 2007). The shallow impervious claypan layer minimizes the potential for nutrient leaching (Blevins et al., 1996; Wilkinson et al., 2000), but results in poor internal drainage and subsequently poor crop yields due to extended periods of saturated soil conditions. Poorly-drained claypan soils in the Midwestern U.S. have not traditionally been tile drained due to the shallow impervious subsoil horizon that requires narrow tile spacing; therefore, subsurface tile drainage was not considered an economically feasible practice (Miller et al., 1914; Spoor and Leeds-Harrison, 1999). Due to recent increased land prices (University of Missouri, 2009), temporary rises in grain prices, and extreme variation in weather, there has been increased public interest in tile draining claypan soils in order to minimize trafficability constraints and manage wet soil conditions that may decrease corn yields (Nelson and Motavalli, 2013) and increase gaseous N fertilizer loss (Nash et al., 2012b).

Installation of subsurface tile drain systems in claypan soils could have a relatively large environmental impact in regard to N loading of surface waters, as without artificial drainage the potential for leaching was low due to the presence of the claypan (Blevins et al., 1996; Wilkinson et al., 2000). Tile drains are typically not placed shallower than 0.9 m. However, the presence of the claypan can require tile drain placement as shallow as 0.6 m, which could increase the potential for N leaching into tile drainage water. Therefore, the objectives of the study were to: 1) quantify the average concentration and annual loss of NO_3^- in tile drain water from a claypan soil, and 2) determine whether MD with PCU could reduce NO_3^- loss in tile water compared to FD with NCU.

MATERIALS AND METHODS

Site Description and Experimental Design

The four-year study was conducted at the University of Missouri's Greenley Research Center near Novelty, MO (40°1'17" N, 92°11'24.9" W). The study was part of a simultaneous study that evaluated the effect of subsurface drainage and N fertilizer source on continuous corn (*Zea mays* L.) production (Chapter 2). Subsurface tile drains and water level control structures (AgriDrain Corporation, Adair, IA) were installed in the summer prior to the initiation of the study in April 2010. Tile drains were installed at a depth of 0.6 m with 6.1 m spacings between tile lines. Plots were separated by a plastic lining (0.15 mm thick) buried 0.7 m deep with raised berms in order to prevent movement of N into adjacent plots. Plots were 9.1 by 61 m in replication one, and 9.1 by 91 m in replication two (Figure 3.1). The study year was defined as the period of time from N fertilizer until the following season's N fertilizer application. The 2013-2014 study year spanned from N fertilizer application (1 May 2013) until 31 December 2013.

The study was a two-way factorial, two replication, randomized complete block design. Treatments included drainage (FD and MD) in combination with N fertilizer sources [NCU and PCU (ESN, Agrium Advanced Technology, Denver, CO)]. Nitrogen fertilizer was applied at 202 kg N ha^{-1} and incorporated into the soil (5 to 10 cm) directly before planting. A Tilloll implement (Landoll Corp., Marysville, KS) was used prior to planting and after harvest. Vertical tillage (Case IH 330, Racine, WI) was used in 2012 for residue management. Field site management including planting dates, harvest dates, and water level control with MD can be found in Table 3.1.

The soil was a Putnam silt loam (fine, smectitic, mesic Vertic Albaqualfs), which contained a claypan subsurface layer at a depth of approximately 0.61 m. Soil samples (composites of three subsamples) were collected from each plot at each depth of 0.0 to 0.3 m, 0.3 to 0.6 m, and 0.6 to 0.9 m in the fall after harvest in each year using a Giddings probe (Windsor, CO). Soil properties combined over plots are presented by year in Table 3.2 and were analyzed using standard soil testing analytical procedures for Missouri (Nathan et al., 2006). Soil NH_4^+-N and NO_3^-N concentrations were converted from mg kg^{-1} to kg ha^{-1} based on soil bulk density measurements taken at the depths of 0-0.3, 0.3-0.6, and 0.6-0.9 m at the field site in 2013. Precipitation data were collected on-site during the study using an automated weather station (Campbell Scientific, Inc., Logan, UT) (Fig. 3.2).

Water Sample Collection, Flow, and Nitrate Loss Measurements

Pressure transducers (American Sensor Technologies, Mount Olive, NJ) measured water height year-round in the water level control structures in each plot. Water height was measured every five minutes and data were stored with dataloggers (Automata, Nevada City, CA). Manual water height readings in the water level control structures were recorded daily over periods of flow in 2012 and 2013 with a Little Dipper (Heron Instruments, Dundas, Ontario) as an additional means of data quality assurance. Flow rates were obtained by subtracting the height of the slides from the water height readings in the control structures and then using the equation:

$$\text{Flow rate (L m}^{-1}\text{)} = 1.4533 * \text{Flow depth (cm)}^2$$

The equation used was obtained through extensive laboratory testing of a V-shaped weir (Chun and Cooke, 2008). Flow rates were then divided by the area drained to determine flow over time and area, which were used to calculate total daily flow from each plot.

Portable automated water samplers (Teledyne ISCO, Lincoln, NE) in conjunction with liquid level actuators (Teledyne ISCO, Lincoln, NE) in 2010 and 2011 were used to collect water samples every six hours when flow was present. Water samples were combined into daily composite samples. In 2012 and 2013, Sigma SD900 portable water samplers (Hach Company, Loveland, CO) were used in conjunction with Sigma 950 flow meters (Hach Company, Loveland, CO) to collect water samples. Water sample collection intensity was the same as in 2010 and 2011; however, approximately 30 days after N fertilization, water samples were combined over three consecutive days to create composite samples. During the winter, water samples were collected manually (approximately every other day) whenever flow was present. Tile drainage water samples were stored in a refrigerator (5 ^{o}C) and filtered (1.5 µm pore size, 934-AH, Whatman Glass Microfiber, General ElectricBio-Sciences, Pittsburgh, PA) prior to being analyzed for NO_3^--N concentration (Quick Chem, 10-107-04-1-F) using an automated ion analyzer (Lachat Quik Chem 8000, Loveland, CO).

Statistical Analysis

Soil N concentration, total water drained, cumulative NO_3^--N loss, and flow-weighted mean concentration of NO_3^--N in the tile drainage water by study year were statistically analyzed for treatment effects using ANOVA and PROC GLM with SAS v9.3 (SAS Institute, 2013). All overall ANOVA analyses including year are presented in Table 3.3. Significant differences in treatment means were determined using Fisher's Protected LSD at P = 0.10 or 0.05.

RESULTS AND DISCUSSION

Precipitation

In the Northeast Missouri region, precipitation distribution is typically bimodal with peaks in the spring (April through June) and late summer (August through September). The distribution and magnitude of precipitation over the four-year study (June 2010 through December 2013) varied considerably compared to the 10-year average prior to the study (Fig 3.2). Precipitation from 2010 to 2013 was generally greater in the spring, lower in the summer and fall, and similar to less over the non-cropping period compared to the 10-year average.

In 2010, heavy precipitation occurred throughout the spring and summer, followed by low precipitation during winter and early spring months (Fig 3.2 and 3.3). Compared to the 10 year average, precipitation was 427 mm greater (65%) from April through September and 175 mm less (53%) from October through March 2011. In 2011, precipitation during the spring was typical for the region, but decreased considerably from July through October, followed by high precipitation in the late fall. Precipitation in 2011 was 238 mm less (60%) from July through October and 130 mm greater (153%) from November through December compared to the 10-year average. Extreme drought conditions were experienced throughout 2012. Precipitation in 2012 was 210 mm less (60%) from May through July and 62 mm less (18%) from August through November. In

2013, wet spring conditions were followed by extreme drought conditions that extended into the fall. Precipitation in 2013 was 224 mm greater (97%) from April through May, which was followed by 218 mm less precipitation (36%) over June through December. Dry conditions experienced over the summer and fall months in three of the four years, generally restricted tile flow to the winter and spring periods.

Soil Nitrogen Concentration

Periods of excessive precipitation and drought over the four-year study affected the soil N concentration after harvest in the fall. Soil NO_3^--N concentration over the depth of 0 to 0.9 m significantly (P = 0.0012) increased each year (2011 to 2013) from 6.9 kg N ha^{-1} in 2011 to 62.9 kg N ha^{-1} in 2013 (Table 3.4). Nitrogen fertilization at rates greater than the required crop uptake needs has been found to result in carry-over N in following seasons (Gast et al., 1978). During the four-year study, 202 kg N ha^{-1} was applied at planting in each year, as is the typical rate require for continuous corn production in the region. However, carry-over N likely occurred in every season due to wet conditions during the short growing season in 2010, and dry summer and fall conditions over 2011-2013 when significant differences in gaseous environmental N loss and corn plant N uptake were reported (Chapter 2 and 4).

Soil NH_4^+-N concentrations when averaged over N fertilizer source and year were significantly (P = 0.0366*)* affected by the drainage systems (FD and MD) over depth (0.0.3, 0.3-0.6, and 0.6-0.9) when averaged over years (Table 3.5). With FD, soil NH_4^+-N concentration increased 8 kg N ha^{-1} over the depth of 0 to 0.3 (22.3 kg N ha^{-1}) to 0.3 to 0.6 m (30.3 kg N ha^{-1}). With MD, soil NH_4^+-N concentration was similar among 0 to 0.3 (23.4 kg N ha^{-1}) and 0.3 to 0.6 (25.7 kg N ha^{-1}) m depth. At a depth of 0.6 to 0.9 m, soil

NH_4^+-N concentration was 10.2 kg N ha^{-1} greater with FD (30.5 kg N ha^{-1}) compared to MD (20.3 kg N ha^{-1}). These results suggest that more consistent tile flow with FD compared to MD may have facilitated the movement of NH_4^+ deeper into soil, while MD may have reduced soil NH_4^+-N concentration through increased plant N uptake.

The concentration of NO_3^--N and total inorganic N (NO_3^--N and NH_4^+-N) in the soil after harvest was significantly ($P \leq 0.0292$) affected by depth when averaged over years (Table 3.5). Soil NO_3^--N concentration decreased 40.7 kg N ha^{-1} from 0 to 0.03 (56.6 kg N ha^{-1}) to 0.6 to 0.9 (15.9 kg N ha^{-1}) m depth. Total soil inorganic N concentration decreased 38.2 kg N ha^{-1} from 0 to 0.3 (79.5 kg N ha^{-1}) to 0.6 to 0.9 (41.3 kg N ha^{-1}) m depth. These results indicated that some N (primarily NH_4^+-N) was able to leach below the tile drains (0.6 m depth) and into the claypan layer, which was presumably due to dry conditions that resulted in cracks in the claypan layer followed by precipitation (Kishne et al., 2009). However, the majority of N accumulated in the top 0.6 m of soil, presumably due to the limited N leaching potential below the claypan.

Tile Water Drained

The total amount of tile water drained was significantly ($P = 0.049$) affected by year and the tile drainage system (Table 3.3). Low precipitation over the summer and fall months in combination with high evapotranspiration rates generally limited tile flow with MD to the months of April through June (Fig. 3.3). During the non-cropping period when tile flow was restricted with MD, tile flow was commonly observed with FD. Precipitation was relatively low over the non-cropping period compared to the spring; however, low evapotranspiration rates and minimal freezing of the soil during this research presumably allowed for considerable tile flow to occur during the non-cropping period. Therefore, annual reduction in water drained with MD compared to FD was large over the four-year study.

In 2010, N fertilizer was not applied until 25 June due to extremely wet conditions in the spring that delayed planting. Although not significant, MD reduced the amount of water drained over the study year by 40% compared to FD (Fig. 3.3). In 2011-2012 and 2012-2013, MD drained 30 to 45 mm of precipitation, which was 73 to 76% less than the 126 to 164 mm drained with FD. Previous reviews of tile drainage studies reported that MD reduced annual water drained 30 to 50% compared to FD (Gilliam et al., 1979; Evans et al., 1995). Relatively high reductions in water drained with MD compared to FD in the study were presumably due to mild to extreme drought conditions during the summer and fall months in combination with wet conditions over the non-cropping period. There was no difference in the total amount of water drained with MD and FD over the final study year (April through December 2013), which was attributed to dry conditions that minimized tile flow throughout the entire period.

Nitrate Concentration and Loss in Tile Drainage Water

Cumulative NO_3^--N loss in tile drainage water was significantly (P = 0.0204) affected by drainage system and study year (Fig. 3.3). Nitrogen fertilizer source did not affect cumulative NO_3^--N loss over the four-year study. Nitrogen presumably was not a limiting factor over the four-year study due to dry summer and fall conditions that limited gaseous N loss and plant N uptake in combination with annual applications of 202 kg N ha^{-1}. Nitrate-N loss ranged from 5 to 8 kg N ha^{-1} in 2010-2011 to 6.7 to 31 kg N ha^{-1} in 2012-2013 due to the drainage system, weather, and accumulating residual soil N (Fig 3.4). Similarly, Gast et al. (1978) reported that annual NO_3^--N loss through tile drainage water increased from 4 to 59 kg N ha^{-1} over a three year continuous corn study with N applied annually at 224 kg N ha^{-1}, which was attributed to carry-over N and increasingly greater soil N concentration over years. The concentration of NO_3^--N typically peaked one month after preplant N applications (5 to 40 mg N L^{-1}) and returned to baseline levels (2.5 to 20 mg L ha^{-1}) during the non-cropping periods. Drury et al. (2009) observed a similar temporal pattern in NO_3^--N concentration in tile drainage water.

The 2010-2011 study year was short due to wet spring conditions that delayed N fertilization and planting until 25 June. Cumulative NO_3^--N loss in the tile drainage water was not significantly ($P \leq 0.05$) different between MD (5 kg N ha^{-1}) and FD (8 kg N ha^{-1}) (Fig. 3.4). Nitrate-N concentration in the tile water did not exceed 5 mg N L^{-1} throughout 2010-2011. Low concentrations of NO_3^--N in tile water and subsequent loss was reported in the first year of a continuous corn study with a similar N application rate, but increased over years due to carry-over N from the previous years (Gast et al., 1978).

In 2011-2012, cumulative NO_3^--N loss in the tile drainage water was reduced 85% with MD (3.8 kg N ha^{-1}) compared to FD (25.5 kg N ha^{-1}) (Fig. 3.4). Previous research studies have reported 32 to 58% annual reductions in NO_3^--N loss in tile drainage water with MD compared to FD, which was attributed to reductions in the annual water drained with MD (Evans et al., 1990; Fogiel and Belcher, 1991; Drury et al., 2009). Although MD reduced the amount of water drained by 72% compared to FD in 2011-2012 (Fig. 3.2), only 27% of the N loss with FD occurred during the non-cropping period when flow was restricted with MD. Consistently lower NO_3^- concentration in the tile water during the free flowing period in the spring reduced NO_3^--N loss by 14.3 kg N ha^{-1} (79%) with MD compared to FD. Carry-over N from the short 2010 growing season and possibly increased denitrification loss over the non-cropping period with MD compared to FD due to wetter soil conditions may have reduced soil N concentration in the spring and subsequent NO_3^--N loss. During the development of MD, it was theorized that wet soil conditions increased denitrification loss over the non-cropping period with use of MD compared to FD that could reduce annual N loss in tile drainage water (Evans et al., 1995; Gilliam et al., 1999). However, reduced concentration of NO_3^- in tile drainage water with MD compared to FD has not previously been observed.

In 2012-2013, cumulative NO_3^--N loss in tile drainage water was reduced by 78% with MD (6.7 kg N ha^{-1}) compared to FD (30.6 kg N ha^{-1}) (Fig. 3.4). Contrary to 2011-2012, NO_3^- concentration in the tile water was generally similar between MD and FD throughout the entire study year. Therefore, the reduction in cumulative NO_3^--N loss in the tile drainage water with MD compared to FD was due previously to a 76% reduction in water drained (Fig. 3.3). Limited flow during the spring and summer months in combination with consistent tile flow with FD over the non-cropping period resulted in a large reduction in annual NO_3^-N loss with MD compared to FD. In climates prone to dry summer months which limit tile flow to spring months with MD, split N application may further reduce annual NO_3^--N loss through tile drainage water. Additionally, high residual soil N in the fall due to carry-over N likely increased the amount of NO_3^--N loss during the non-cropping period with FD.

Nitrate-N loss in tile drainage water was minimal in 2013 (1 May through 31 December 2013) compared to 2011-2012 and 2012-2013 due to extreme drought conditions throughout the year that limited tile flow (Fig. 3.3 and 3.4). Cumulative NO_3^--N loss in the tile drainage water was relatively low and not significantly different between MD (3.2 kg N ha^{-1}) and FD (7.1 kg N ha^{-1}) in 2013. Based on 2012-2013, the potential for NO_3^--N loss with FD over the non-cropping period may have been large because of high residual soil N in the fall of 2013 (Table 3.4) which was probably due to limited N loss and plant N uptake over the 2013 growing season.

Flow-Weighted Mean Concentration of Nitrate in Tile Drainage Water

Drainage water management systems and N fertilizer source were not found to significantly affect the flow-weighted mean concentration of NO_3-N throughout the four-year study (Table 3.3). Significant differences ($P < 0.0001$) in the flow-weighted mean concentration of NO_3^- were observed between study years (Table 3.6). Average flow-weighted concentrations of NO_3^{-1}-N in study years were 5.4 (2010-2011), 11.9 (2011-2012), 23.6 (2012-2013), and 27.2 mg N L^{-1} (2013). Previous tile drainage research in corn production has reported annual flow-weighted mean concentration of NO_3^--N in tile water in the range of 6 to 43 mg N L^{-1} (Gast et al, 1978; Baker and Johnson, 1981; Drury et al., 1993; Randall and Vetsch, 2005). The greater flow-weighted mean concentration of NO_3^{-1}-N observed in the tile water in 2012-2013 and 2013-2014 compared to 2010-2011 and 2011-2012 can be attributed to drier growing season conditions that presumably limited corn plant uptake, N removal, and gaseous N loss (Nash et al., 2014), tile drainage flow, and accumulating residual soil N (Table 3.4). Similarly, Drury (1993) observed an approximate 30% increase in annual flow-weighted mean concentration of NO_3^--N in the tile water in a year with 50% less water drained.

CONCLUSIONS

Mild to extreme drought conditions throughout three of the four growing seasons likely limited environmental N loss and corn N uptake that would remove soil N resulting in carry-over N and subsequently high soil N concentrations. As a result, N was presumably not a limiting factor over the four-year study and masked the response in NO_3^- concentration and loss due to differences in N fertilizer source (PCU and NCU). Adoption of MD over FD may be an effective strategy to reduce N loss in tile drainage water in claypan soils, particularly in high N input production systems such as continuous corn. Contrary to most other soils, leaching of N below the tile drains was restricted due to the presence of the claypan layer which could exacerbate the potential for N loss through tile drainage water. However, due to limited tile flow over the four-year study, the annual flow-weighted mean concentrations and annual loss of NO_3^--N in tile drainage water did not exceed that reported in previous tile drainage research in corn production with similar N application rates.

Limited tile flow during the growing season resulted in high reductions in annual water drained and subsequent N loss with MD compared to FD. The annual reduction in the amount of water drained with MD reduced NO_3^--N loss by 78% compared to FD in one study year, which was considerably higher than commonly reported. However, an 85% reduction in annual NO_3^--N loss in another year with MD compared to FD was only partially due to a reduction in the annual amount of water drained. Lower N concentration with MD compared to FD during the spring when flow was similar was possibly due to increased denitrification loss with wetter soil conditions with MD compared to FD during the preceding non-cropping period. Additional research should evaluate the use of a split N application with MD to further reduce annual NO_3^--N loss through tile drainage water.

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Table 3.1. Field site management including fertilizer applications, plant and harvest dates, and water level control management with managed drainage over the four-year study.

Field site management	2010	2011‡	2012	2013
Maintenance fertilizer application date†	10 April 2010	------------	12 April 2012	------------
N-P-K rate (kg ha^{-1})	36-78-279	------------	18-39-112	------------
N fertilizer application	25 June 2010	5 May 2011	4 April 2012	1 May 2013
Rate (kg N ha^{-1})	202	202	202	202
Planting date	25 June 2010	5 May 2011	4 April 2012	1 May 2013
Rate (seeds ha^{-1})	74,000	74,000	74,000	74,000
Harvest date	5 Nov. 2010	30 Oct. 2011	5 Sept. 2012	12 Oct. 2013
Water level control – Free drainage mode	10 Mar. 2010	1 April 2011	27 May 2012	8 April 2013
Water level control – Managed drainage mode§	24 Sept. 2010	11 July 2011	5 June 2012	14 June 2013

† Maintenance fertilizer applied was mono-ammonium phosphate.
‡ In 2011, managed drainage treatments were taken out of managed drainage mode prior to harvest (30 Sept. 2011) and put back in managed drainage mode after harvest (2 Nov. 2011).
§ Managed drainage treatments remained in managed drainage mode until the spring of the following year.

Table 3.2. Selected soil chemical properties from fall soil sampling at a depth of 0 to 0.3 m in 2010, 2011, 2012, and 2013. Data were averaged over tile drainage systems and N fertilizer source treatments.

		Year‡			
Soil property†	Units	2010	2011	2012	2013
pH (0.01 M $CaCl_2$)	------------	5.6 ± 0.3§	6.3 ± 0.2	6.1 ± 0.2	5.8 ± 0.5
N.A.	$cmol_c\ kg^{-1}$	1.8 ± 0.5	1.2 ± 0.5	1.9 ± 0.4	2.1 ± 1.4
O.M.	$g\ kg^{-1}$	23 ± 5	26 ± 2	22 ± 6	22 ± 4
Bray I P	$kg\ ha^{-1}$	88 ± 20	64 ± 26	81 ± 27	85 ± 37
Exch. Ca	$kg\ ha^{-1}$	6064 ± 1045	5174 ± 501	4763 ± 921	5012 ± 1105
Exch. Mg	$kg\ ha^{-1}$	583 ± 91	522 ± 95	523 ± 76	513 ± 86
Exch. K	$kg\ ha^{-1}$	481 ± 99	409 ± 92	450 ± 141	474 ± 157
CEC	$cmol_c\ kg^{-1}$	18 ± 3	15 ± 2	15 ± 2	16 ± 3
NO_3^--N	$kg\ N\ ha^{-1}$	19.8 ± 3.6	11.2 ± 8.7	77.6 ± 97.4	81.0 ± 42.8
NH_4^+-N	$kg\ N\ ha^{-1}$	12.3 ± 0.9	25.3 ± 3.6	18.9 ± 5.8	24.4 ± 7.9

† Abbreviations: Exch. = exchangeable; N.A. = neutralizable acidity; O.M. = organic matter; CEC = cation exchange capacity.

‡ Soil samples were averaged over all N fertilizer source and drainage treatments (n = 8).

§ Numbers following mean values represents plus or minus one standard deviation.

Table 3.3. ANOVA table summary of soil N concentration, water drained, NO_3^--N loss, and flow-weighted mean (FWM) associated with subsurface tile drainage from 2010-2013.

	Soil N concentration[†]			Subsurface tile drainage		
	NO_3^--N	NH_4^+-N	Total inorganic N	Water drained	NO_3^--N loss	FWM
Source	*P* > *F*	*P* > *F*	*P* > *F*	*P* > *F*	*P* > *F*	*P* > *F*
Rep	0.1231	0.1271	0.1806	0.5916	0.5425	0.2896
Year	0.0012	0.4078	0.0007	0.0002	0.0080	<.0001
Depth	0.0215	0.0619	0.0292	NA[‡]	NA	NA
Drainage	0.1559	0.0116	0.0685	<.0001	0.0002	0.9337
N Source	0.9267	0.2996	0.8001	0.9092	0.9449	0.1404
Depth x Drainage	0.6730	0.0366	0.8617	NA	NA	NA
Depth x N Source	0.9225	0.1633	0.9938	NA	NA	NA
Drainage x N Source	0.4269	0.7458	0.3921	0.6786	0.8697	0.1109
Year x Depth	0.3796	0.2504	0.5228	NA	NA	NA
Year x Drainage	0.5429	0.6937	0.4678	0.0490	0.0204	0.1394
Year x N Source	0.9119	0.4001	0.8486	0.8940	0.9615	0.4135
Depth x Drainage x N Source	0.7418	0.3799	0.8493	NA	NA	NA
Year x Depth x Drainage	0.8762	0.3676	0.8830	NA	NA	NA
Year x Depth x N Source	0.8762	0.2300	0.9984	NA	NA	NA
Year x Drainage x N Source	0.7465	0.3921	0.6429	0.9287	0.7598	0.5325
Year x Depth x Drainage x N Source	0.9566	0.6805	0.9546	NA	NA	NA

† Soil N concentration was collected and analyzed after harvest in 2011-2013.

‡ Abbreviation: NA = not applicable.

Table 3.4. Soil NO_3^--N, NH_4^+-N, and total inorganic N concentration after harvest in 2011-2013. Data were averaged over 0 to 0.9 m depth.

Year†	Soil N concentration		
	- kg NO_3^--N ha^{-1} -	- kg NH_4^+-N ha^{-1} -	- kg N ha^{-1} -
2011	6.9	25.1	32.0
2012	38.0	24.2	62.2
2013	62.9	27.0	89.9
LSD (*P=0.05*)	23.6	NS	23.3

† Abbreviations: LSD = least significant difference; NS = not significant.

Table 3.5. Effect of drainage water management and depth on soil NO_3^--N, NH_4^+-N, and total inorganic N after harvest. Data were averaged over 2011-2013.

Depth (m) †	Soil N concentration			
		FD	MD	
	- kg NO_3^--N ha^{-1} -	- kg NH_4^+-N ha^{-1} -		- kg N ha^{-1} -
0-0.3	56.6	22.3	23.4	79.5
0.3-0.6	35.3	30.3	25.7	63.3
0.6-0.9	15.9	30.5	20.3	41.3
LSD (*P=0.05*)	23.6	6.0		23.3

† Abbreviations: FD = free drainage; LSD = least significant difference; MD = managed drainage.

Table 3.6. The main effect of year, and the interaction of drainage and N fertilizer source on flow weighted mean concentration of NO_3^--N in tile drainage water.

Year[†]	Flow weighted mean	Drainage[‡]	N Source	Flow weighted mean
	--- mg NO_3^--N L^{-1} ---			--- mg NO_3^--N L^{-1} ---
2010-11	5.4	FD	NCU	17.0
2011-12	11.9	FD	PCU	17.2
2012-13	23.6	MD	NCU	19.5
2013-14[§]	27.2	MD	PCU	14.4
LSD (*P=0.05*)	4.7	LSD (*P=0.10*)		NS

[†] Year represented the period of time from preplant N fertilization until the N fertilization in the next year.
[‡] Abbreviations: FD = free drainage; LSD = least significant difference; MD = managed drainage; NCU = non-coated urea; PCU = polymer-coated urea.
[§] The 2013-14 study year spanned from preplant N fertilization through 31 December 2013.

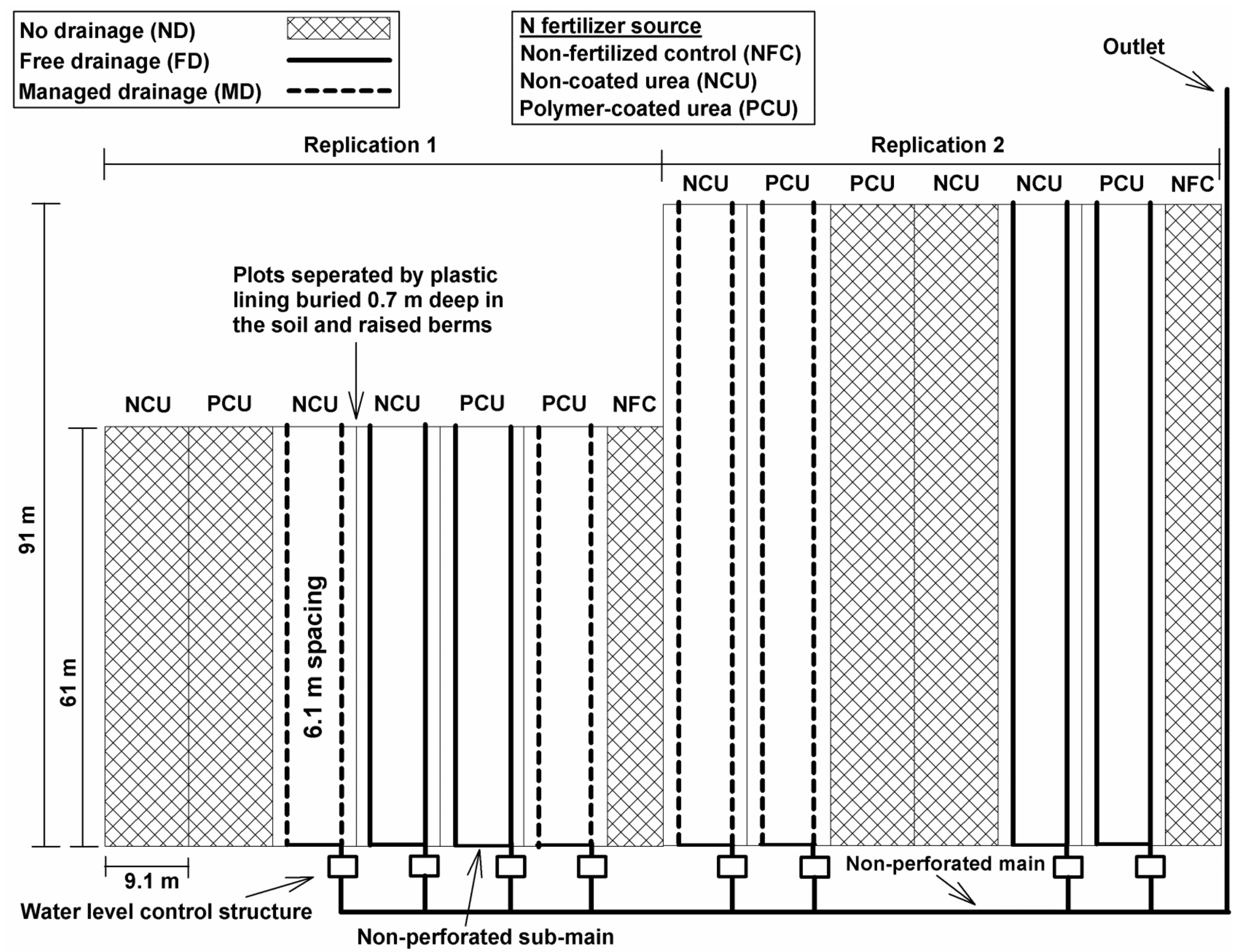

Figure 3.1. Field layout and plot treatments including the subsurface drainage system design.

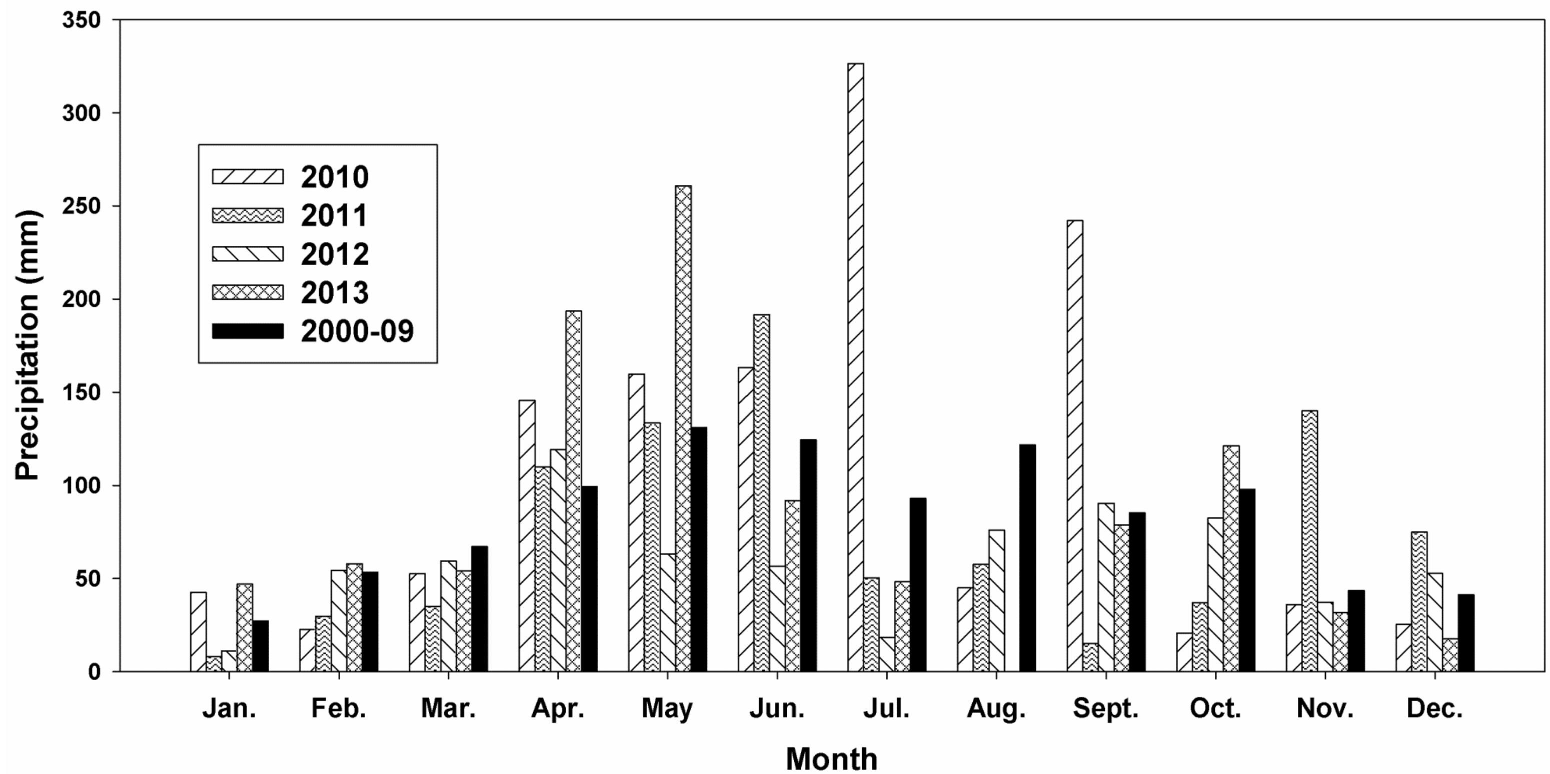

Figure 3.2. Average monthly precipitation over the four-year study (2010-2013) and the 10 year average (2000-2009).

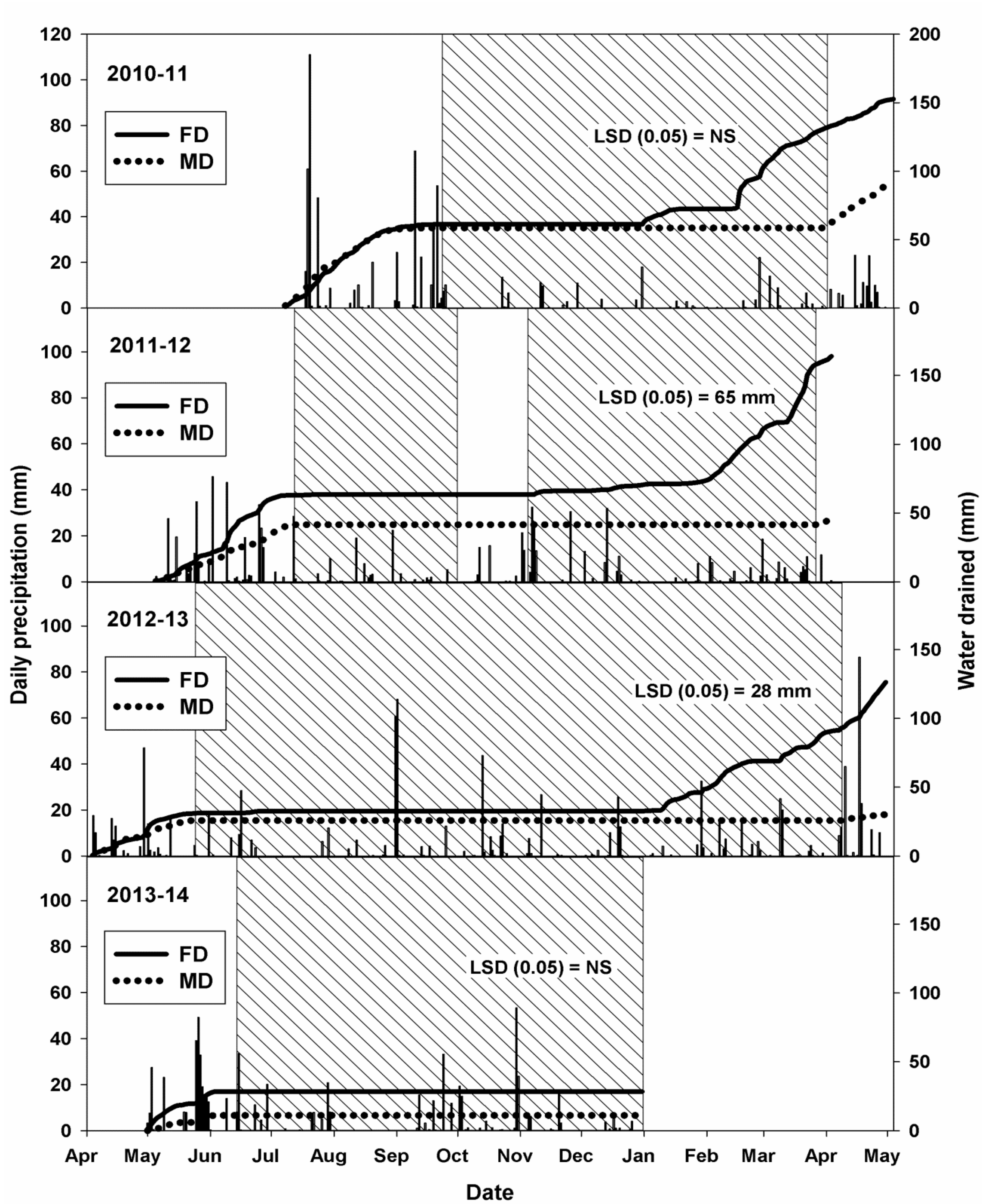

Figure 3.3. Daily precipitation (bars) and cumulative tile water drained (lines) by tile drainage system (FD = free drainage system and MD = managed drainage system) and years. The start of each study year corresponds to the spring N application. Shaded areas represent the period of time that MD treatments were in managed drainage mode. NS = not significant.

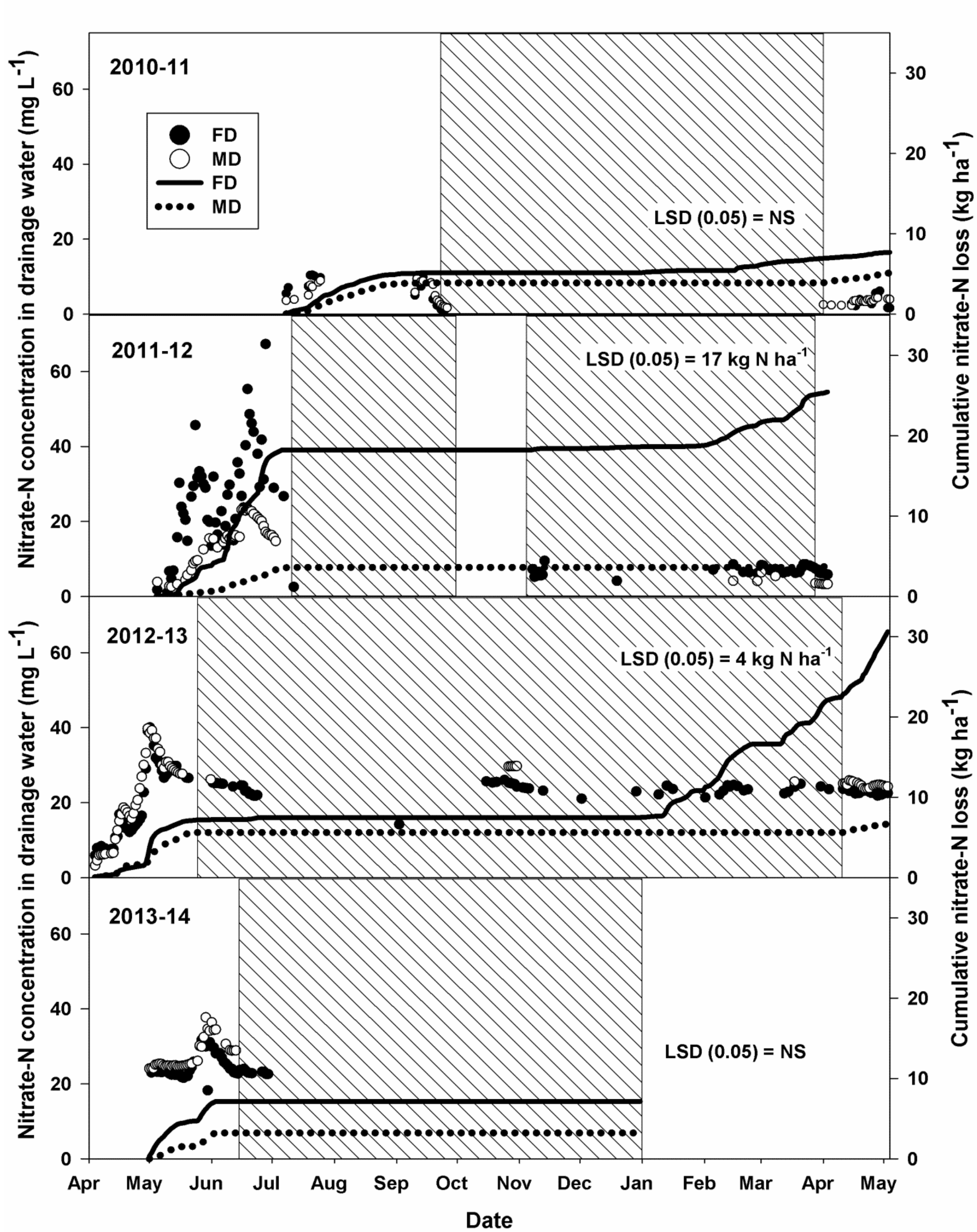

Figure 3.4. Daily concentration of nitrate-N in tile drainage water (circles) and cumulative nitrate-N loss (lines) by tile drainage treatment (FD = free drainage system and MD = managed drainage system) and years. The start of each study year corresponds to the spring N application. Shaded areas represent the period of time that MD treatments were in managed drainage mode. NS = not significant.

CHAPTER 4

AMMONIA AND NITROUS OXIDE GAS LOSS WITH SUBSURFACE DRAINAGE AND POLYMER-COATED UREA FERTILIZER IN A POORLY-DRAINED SOIL

ABSTRACT

Gaseous N loss in the form of ammonia (NH_3) and nitrous oxide (N_2O) from applied urea fertilizer on poorly-drained soils can diminish agronomic production and environmental quality in the absence of best management practices such as managed subsurface tile drainage and use of controlled-release fertilizers. The objective of the study was to determine how subsurface tile drainage and applications of polymer-coated urea (PCU) affect soil N_2O emissions and N fertilizer-induced NH_3 volatilization loss from a claypan soil. Drainage water management treatments consisted of conventional subsurface tile drainage, managed subsurface tile drainage, and no-drainage in combination with N fertilizer source [non-coated urea (NCU) and PCU]. Subsurface drainage treatments did not significantly ($P \leq 0.05$) affect cumulative soil N_2O emissions and NH_3 volatilization loss compared to no-drainage. Averaged over 2010-2013, cumulative soil N_2O emissions from PCU and NCU were 2 and 4% of applied fertilizer N, respectively. Yield-scaled soil N_2O emissions were reduced 53% with PCU compared to NCU. The percent fertilizer loss from NH_3 volatilization was significantly ($P \leq 0.05$) reduced from 2.8% with NCU to 0.8% with PCU. These results suggest that use of PCU may assist in reducing cumulative losses of N_2O and NH_3 from poorly drained claypan soils, but drainage systems operating under this study's environmental conditions did not contribute to lowering gaseous N losses.

INTRODUCTION

Gaseous N loss in the form of ammonia (NH_3) and nitrous oxide (N_2O) from applied urea fertilizer on poorly-drained claypan soils can reduce crop production and pollute the environment. Claypan soils in the north-central United States are characterized as having a soil layer with at least 100% greater clay content than the soil horizon directly above it (Jung et al., 2006; Myers et al., 2007). The claypan layer's low permeability limits these soils' internal drainage and their potential for nitrate leaching. The majority of environmental N loss occurs through NH_3 volatilization, denitrification (Blevins et al., 1996; Wilkinson et al., 2000), and lateral flow. Therefore, maintaining high production and low environmental impact requires that farmers manage claypan soils in ways that lower the potential for gaseous N loss.

Loss of ammonia gas from urea fertilizer can occur during urea hydrolysis in where microbes drive N transformation of urea to ammonium. Studies have evaluated ways in which soil properties, environmental conditions, and management affect urea hydrolysis and the amount of soil NH_3 volatilization loss (Moe, 1967; Overrein and Moe, 1967). Soil properties directly influence microbial activity and subsequent urea hydrolysis and NH_3 diffusion out of the soil. Greater soil pH, temperature, soluble carbon, and decreased soil H^+ buffering capacity, cation exchange capacity, and the drying down of soils typically results in a higher potential for soil NH_3 volatilization (Al-Kanani et al., 1991; Chantigny et al., 2004; Ernst and Massey, 1960; Ferguson et al., 1984). Nathan and Malzer (1994) found a positive correlation of atmospheric temperature and wind speed with the rate of NH_3 volatilization. In contrast, they also observed that relative humidity was negatively correlated with the rate of NH_3 volatilization. Many studies show that several management practices reduce soil NH_3 volatilization loss from applied urea fertilizers (Holcomb III et al., 2011; Nathan and Malzer, 1994; Rochette et al., 2013). The rate of NH_3 volatilization loss decreased with N fertilizer application depth in the soil (Overrein and Moe, 1967; Rochette et al., 2013), while including a urease inhibitor reduced volatilization loss 25 to 80% (Engel et al., 2011; Zerpa and Fox, 2011). Surface application of urea fertilizer prior to a rainfall mitigates much of the potential for volatilization loss (Jantalia et al., 2012; Kissel et al., 2004).

Ammonia volatilization loss typically ranges from 0 to 60% of applied urea-N fertilizers depending on climate, management, soil type, and production system (Holcomb III et al., 2011; Kissel et al., 2009; Singh et al., 2012; Vaio et al., 2008). The wide range in NH_3 loss from applied N further indicates the complexity of soil NH_3 volatilization loss in field settings. Unless environmental and soil conditions with a high potential for volatilization loss are managed appropriately, significant loss of applied urea-N will result that may negatively impact crop production.

Denitrification loss and subsequent soil N_2O emissions typically are greater with increased soil moisture and soil temperature (Sexstone et al., 1985). However, before denitrification loss occurs, urea-based fertilizers must first be converted to nitrate through urea hydrolysis and nitrification. Therefore, the rate of denitrification ties closely to soil microbial activity (Six et al., 2004), as well as soil wetting and drying cycles that foster the aerobic and anaerobic soil conditions required for nitrification and denitrification to occur, respectively (Aulakh et al., 1991). Claypan soils can exhibit a high potential for denitrification loss due to high temperatures and extended periods of saturation, particularly early in the growing season when plant N uptake is minimal and rainfall typically exceeds the rate of evapotranspiration.

In corn studies set in varied climates, soil types, and management practices soil N_2O emissions rarely exceeded 2% of applied N fertilizer (Drury et al., 2006; Halvorson et al., 2010b; Halvorson and Del Grosso, 2013; Venterea et al., 2010). However, N loss as N_2O gas from a claypan soil consistently exceeded 2% of applied N fertilizer and at times was as high as 4% (Nash et al., 2012b). Additionally, Nash et al. (2012b) reported that alternative management practices, such as strip-tillage with deep placement and PCU, did not reduce soil N_2O emissions as in other studies (Drury et al., 2006; Halvorson et al., 2011).

Reducing soil N_2O emissions from agronomic practices is important because N_2O, a greenhouse gas linked to ozone depletion, has a global warming potential 310 times that of carbon dioxide, and has an atmospheric residence time of approximately 120 years (Smith et al., 2007; USEPA, 2011). Soil N_2O emissions associated with agricultural practices were the largest source (69%) of N_2O emissions in the U.S. (USEPA, 2011). From 1990 to 2011, agricultural soil N_2O emissions increased 9% (USEPA, 2011). Due to the high potential for denitrification loss and subsequent N_2O emissions from claypan soils, farmers can minimize negative effects on production and the environment by managing soils in ways that reduce the potential for gaseous N loss.

Installing subsurface tile drainage in a claypan soil could improve soil drainage and minimize extended periods of soil saturation that lead to denitrification loss and subsequent N_2O emissions. Nelson et al. (2009) found that tile drainage in a poorly drained claypan soil increased corn (*Zea mays* L.) yields and increased plant N uptake up to 46%. The combined effect of minimizing saturated soil conditions and increased plant N uptake with tile drainage may significantly lower soil N_2O emissions while increasing yields in a claypan soil. However, using tile drainage to maintain soil moisture conditions at field capacity for longer periods may increase the potential for soil NH_3 volatilization loss. No published research has evaluated the impact of subsurface tile drainage on gaseous N loss such as NH_3 and N_2O.

Controlled release urea-N fertilizers, such as polymer-coated urea (PCU), have reduced environmental N loss compared to granular urea (NCU) (Halvorson et al., 2014; Xu et al., 2013). Temperature and soil moisture affected the rate of urea-N released into the soil from PCU (Fujinuma et al., 2009). For PCU applied in April, urea-N released by June was less than 30% when broadcast on the soil surface (Nash et al., 2012a) and less than 40% when incorporated in the soil at a shallow depth (2-5 cm) (Nelson et al., 2014). Thus, increased contact of PCU with the soil through incorporation may increase the rate of release. However, this technology's slower release of urea-N could reduce soil gaseous N loss by limiting the availability of applied N until later in the growing season when soil conditions are less conducive to volatilization or denitrification and when plant N uptake is greater.

Little research has evaluated the effect of controlled-release urea fertilizers on soil NH_3 volatilization compared to NCU. Matocha (1976) found that slow-release, sulfur-coated urea fertilizers reduced NH_3 volatilization by 9.9 times that of NCU. However, Jantalia et al. (2012) reported a 38% increase in volatilization loss with PCU compared to NCU when fertilizers were broadcast-applied, which may have been due to irrigation water being applied directly after N application.

Studies show that application of PCU can reduce soil N_2O emissions compared to applications of dry, granular urea (NCU). In irrigated corn in Colorado, PCU reduced soil N_2O emissions 34 to 48% compared to NCU (Halvorson et al., 2010a; Halvorson and Del Grosso, 2013). We hypothesize that combining PCU with subsurface tile drainage could have a synergistic benefit and could reduce the high emission rate of N_2O gas from claypan soils under corn-based cropping systems.

Numerous studies have evaluated the impact of PCU on soil gaseous N emissions, but no studies have evaluated the effect of subsurface tile drainage on the gaseous N emissions. The objective of the study was to determine the impact of subsurface tile drainage and application of PCU on soil N_2O emissions and NH_3 volatilization loss from a claypan soil.

MATERIALS AND METHODS

Site Description and Experimental Design

A four-year study began in June 2010 and ended in September 2013 in Northeast Missouri's claypan region at the University of Missouri's Greenley Memorial Research Center (40°1'17" N, 92°11'24.9" W). The soil series was a Putnam silt loam (fine, smectitic, mesic Vertic Albaqualfs) with a claypan layer at a depth of approximately 0.61 m. Soil properties (Table 4.1) were determined by averaging over soil samples taken from all plots (three sub-samples per plot) at three depths (0-0.3, 0.3-0.6, 0.6-0.9 m) with a Giddings probe (Giddings Machine Company, Windsor, CO) following harvest in each season. Nitrogen applied at 202 kg N ha^{-1} annually in combination with dry conditions over the summer in 2011, 2012, and 2013 presumably limited plant N uptake and environmental N loss that resulted in a buildup of residual soil N over the four-year study. Analyses of soil samples followed standard soil testing analytical procedures for Missouri (Nathan et al., 2006). Soil NH_4^+-N and NO_3^-N concentrations were converted from mg kg^{-1} to kg ha^{-1} based on soil bulk density measurements taken at the depths of 0-0.3, 0.3-0.6, and 0.6-0.9 m at the field site in 2013. Rainfall was measured on-site using an automated weather station (Campbell Scientific, Inc., Logan, UT).

The field site was in continuous corn (*Zea mays* L.) production with spring and fall tillage using a Tilloll field cultivator (Landoll Corp., Marysville, KS). In the fall of 2012, vertical tillage (Case IH 330, Racine, WI) was used for management of residue. Corn hybrid DeKalb 62-54 VT3 was planted in 2010, 2011, and 2012, and DeKalb 62-97 RIB in 2013 (Fig. 1). Corn was seeded at 74,100 seeds ha^{-1} in 76-cm wide rows. The experiment was a 2 x 3 factorial arranged in a randomized complete block design with two replications. A non-fertilized, non-drained control was included in each replication as a baseline reference of gaseous N emissions. Treatments consisted of conventional subsurface tile drainage, managed subsurface tile drainage, and no-drainage in combination with N fertilizer source [i.e., NCU and PCU (ESN, Agrium Advanced Technology, Denver, CO)] applied at 202 kg N ha^{-1}. Immediately prior to planting, N fertilizers were broadcast applied with hand spreaders, and incorporated into the soil (5-10 cm) with tillage. Plot treatments remained the same over the four years of this experiment and were maintained at the same field location. Plots were 9 m wide by 61 and 91.5 m long in replications one and two, respectively. Tile drainage and control structures were installed in August 2009 at a 0.6 m depth at 6 m spacing. Plots were separated by plastic lining in the soil (i.e., 0.7 m depth) and berms on the surface to impede any potential movement of N fertilizer or water laterally between treatments.

Field Measurements of Nitrous Oxide and Ammonia Gas Emissions

In-field soil N_2O flux was determined following the USDA-ARS GRACEnet Chamber-based Trace Gas Flux Measurement Protocol (Parkin et al., 2003). This study's vented, static ring chamber design, sampling procedure, and soil N_2O flux and emission calculations are detailed in Nash et al. (2012b). Differences in this study's sampling procedure included using a 0, 20, and 40-minute sampling interval during the growing season (April through October) on an average of three times a week for two months after N application. During summer, soil N_2O flux measurements were taken less frequently as soil conditions generally became drier. Gas sampling occurred monthly during the winters of 2012 and 2013 at sampling intervals of 0, 30, 60 minutes. Soil N_2O flux was not detected during the winters of 2012 or 2013, and so these data are not presented. Corn yields from the study, presented by Nash (2014) were used to determine yield-scaled soil N_2O emissions.

In-field measurements of ammonia volatilization loss were measured for 42 days after N fertilizer application. Measurements were made using a semi-open static system similar to Griggs et al. (2007), which was comprised of a clear plexiglass chamber and polyurethane foam sorbers. Jantalia et al. (2012) evaluated the semi-open static chamber design and found it adequate for measuring soil NH_3 volatilization loss. Each plot contained two chambers, 13 (diameter) by 75 cm (height), driven 15 cm into the soil, and placed in the inner planted rows approximately 7.6 m from the ends of the plot. Polyurethane foam sorbers (2.5 cm thick) were washed with 0.73 M H_3PO_4, rinsed with deionized water, and then impregnated with 35 mL of a 0.73 M H_3PO_4 / 33% glycerol (v/v) solution. Two foam sorbers were placed in each chamber, 0 and 15 cm from the top of the chamber, and replaced weekly. The foam sorber placed at the top of the chamber trapped ambient NH_3, while the sorber placed 15 cm lower trapped NH_3 emitted from the soil. Sorbers were soaked overnight in a 100 mL 2 M KCl solution and drained into a sample bottle for storage at 5^{o}C. Samples were analyzed for NH_4^+-N concentration (QuikChem 12-107-06-2-A) using an automated ion analyzer (Lachat Quik Chem 8000, Loveland, CO). Blank samples of KCl were analyzed from the solution used throughout each study year as a quality control check. Subsurface drainage treatments were not found to affect NH_3 volatilization loss throughout this study. Therefore, volatilization loss from the non-drained/non-fertilized plots were used to estimate N fertilizer-induced loss from all N source and drainage treatment combinations.

Statistical Analysis

A two-way factorial, randomized complete block ANOVA with year was used to determine significant differences among treatments with cumulative growing season soil N_2O emissions, yield-scaled emissions, cumulative growing season and total (summed over four years) fertilizer-induced NH_3 volatilization loss, and percent loss of applied N. Non-drained, non-fertilized controls were not included in the statistical analyses. Subsurface drainage treatments were not significant ($P \leq 0.05$) in any of the statistical analyses. A two-way interaction of year x N fertilizer source was only significantly ($P \leq 0.05$) affected fertilizer-induced NH_3 volatilization loss and applied N loss. The single factor of N fertilizer source was significant ($P \leq 0.05$) with all soil N_2O emission analyses, total fertilizer-induced NH_3 volatilization loss and applied N loss analysis. The statistical program, SAS v9.3 with PROC GLM and Fischer's Protected LSD was used to separate means and determine significant treatment effects (SAS Institute, 2013).

RESULTS AND DISCUSSION

Rainfall

Total rainfall from April through October, 2010-2013 ranged from 1090 mm in 2010 to 510 mm in 2012 (Fig. 4.1). The 10-year average for April through October prior to 2010 was 750 mm (data not presented). The 2010 growing season was wet compared to the 10-year average, and 2011, 2012, and 2013 generally were dry through the summer months. For the April-through-October period, 2010 received 45% more rainfall than the ten-year average, and 2011 and 2012, received 20 and 32% less rainfall, respectively. The 2013 growing season received a similar total amount of rainfall compared to the ten-year average for April through October, but rainfall distribution of rainfall differed, and in summer the site experienced a flash drought.

In spring (April through June), the Midwestern Corn Belt can experience high soil moisture conditions due to a high amount of rainfall and low evapotranspiration rates. The opposite is true during the summer period of July through October (Mclsaac et al., 2010; Yeh et al., 1998**)**. Total rainfall for April through June was 33% more in 2010 and 30% less in 2012, compared to the 10-year average (Fig. 4.1). Excessive rainfall in the spring of 2010 delayed N application, tillage, and planting until June 25. During summer (July through October), 56% more rainfall occurred in 2010, and 58 and 34% less rainfall occurred in 2011 and 2012 compared to the ten-year average, respectively. The 2013 growing season received 55% more rainfall from April through June and 34% less rainfall from July through October compared to the 10-year average.

Soil Nitrous Oxide Flux and Cumulative Emissions

Temporal response differences in daily soil N_2O flux among NCU and PCU were not observed during the study's four growing seasons (Fig. 4.2). This result contradicts numerous studies that have observed delayed soil N_2O emissions with PCU compared to NCU (Halvorson and Del Grosso 2012; Halvorson and Del Grosso 2013; Halvorson et al., 2010b; Nash et al., 2012b). However, the magnitude of soil N_2O emissions from PCU was less than NCU throughout the growing seasons. Halvorson et al. (2008) observed a similar temporal response in daily soil N_2O flux, which occurred 29 (2012) to 41 days (2011) after N fertilization. During these peaks in soil N_2O flux, values for NCU flux were 56% (2013) to 150% (2011) greater than PCU. Flux values from fertilized treatments returned to baseline levels 46 to 50 days after N fertilization in three of the four growing seasons. This study's temporal response of soil N_2O flux contradicted another study of PCU and NCU on a claypan soil in which soil N_2O flux peaked and the returned to the baseline level between 40 to 60 days and 60 to 80 days after N application, respectively (Nash et al., 2012b). The temporal shift of soil N_2O flux earlier into the growing season indicated that increasing fertilizer N contact with soil through incorporation with tillage in claypan soil may exacerbate the early-season potential for N_2O emissions as compared to strip-tillage/deep banding placement and no-till/surface broadcasting of urea fertilizers. The earlier flux may also explain why the reduction in soil N_2O flux between PCU and NCU was greater in this study. However, the relatively short period of elevated soil N_2O flux commonly reported illustrates how the controlled release properties of PCU can mitigate the potential of soil N_2O emissions.

Subsurface drainage treatments did not significantly ($P \leq 0.05$) affect cumulative soil N_2O emissions throughout the study (data not presented). However, a significant reduction in cumulative soil N_2O emissions with PCU compared to NCU was observed in each growing season (Fig. 4.2). These results were similar to several studies of irrigated corn in Colorado under varying tillage and N placement management practices (Halvorson et al., 2014; Hatfield and Venterea, 2014). However, a study in Minnesota on a well-drained soil with management practices similar to this study reported increased cumulative soil N_2O emissions with PCU compared to NCU (Venterea et al., 2011). The potential for reduced soil N_2O emissions with PCU compared to NCU appeared to increase with wetter soil conditions due to early-season high rainfall, irrigation inputs, and/or poor drainage.

Cumulative soil N_2O emission over a growing season with NCU ranged from 7.2 kg N_2O-N ha^{-1} (2010) to 10.6 kg N_2O-N ha^{-1} (2013). With PCU, cumulative emissions over a growing season ranged from 2.9 kg N_2O-N ha^{-1} (2010) to 5.7 kg N_2O-N ha^{-1} (2013). The greatest decrease in cumulative soil N_2O emissions with PCU compared to NCU was 60% in 2010, and the smallest reduction was 33% in 2012.

When averaged across the 2010-2013 growing season, cumulative soil N_2O emissions were 47% less with PCU compared to NCU (Fig. 4.3). Cumulative soil N_2O emissions from PCU and NCU averaged 2 and 4% of applied N, respectively. Similarly, a corn study on a claypan soil also found that soil N_2O emissions accounted for 2 to 4% of applied N (Nash et al., 2012b). In most environments, N fertilizer loss as N_2O typically has not exceeded 2% of applied N (Halvorson and Del Grosso, 2012; Omonode et al., 2011; Venterea et al., 2010). Even with the addition of tile drainage, greater fertilizer N loss as N_2O gas presumably was due to high rainfall in the spring and poor internal drainage of claypan soils.

Yield-Scaled Soil Nitrous Oxide Emissions

Drainage treatments did not significantly ($P \leq 0.05$) affect soil N_2O emissions, but N fertilizer source and year did (data not presented). When averaged across 2010-2013 growing seasons, baseline yield-scaled soil N_2O emission from the non-drained, non-treated control averaged 0.3 kg N_2O-N Mg corn grain^{-1} season^{-1}. With fertilized treatments, yield-scaled soil N_2O emissions were 0.9 and 1.9 kg N_2O-N Mg corn grain^{-1} season^{-1} with PCU and NCU, respectively. This was a 53% reduction with PCU compared to NCU. When averaged over drainage and N fertilizer treatments, yield-scaled soil N_2O emissions were significantly lower in 2010 and 2013 (data not presented); this was not a function of soil N_2O emissions, but rather of lower overall yield (data not presented).

Contrary to the findings of this study, a three-year corn study in Minnesota with conventional tillage and different broadcast N fertilizer sources (at 146 kg N ha^{-1}) found that PCU increased yield-scaled soil N_2O emissions by 35% compared to NCU (Venterea et al., 2011). Contrasting responses in field-scaled soil N_2O emissions were likely due to greater rainfall and reduced internal drainage associated with a claypan soil. A similar response was observed in yields between PCU and NCU, where PCU increased corn yield compared to NCU only in wet, low-lying landscape positions (Noellsch et al., 2009). Numerous irrigated, no-till and strip-till corn studies in Colorado have reported yield-scaled N_2O emission responses with NCU and PCU that parallel this study (Halvorson et al., 2010a; Halvorson and Grosso 2012; Halvorson and Grosso 2013;

Halvorson et al., 2011). Among these studies, yield-scaled soil N_2O emissions with PCU were 20 to 52% less than with NCU. Similar yield-scaled soil N_2O emission response to NCU and PCU in the Colorado studies presumably was due to irrigation inputs that maintained elevated soil moisture throughout the growing season. In comparison to the Minnesota and Colorado studies, this study's site likely had a greater potential for denitrification loss and lower corn yield potential. Site differences resulted in up to a threefold increase in soil N_2O emissions per unit corn grain produced in this study compared to the studies in Minnesota and Colorado. This finding reinforced the importance of reducing agricultural soil N_2O emissions from claypan soils through best crop management practices.

Fertilizer-Induced Ammonia Volatilization Loss

The occurrence of rainfall and incorporation of N fertilizer directly after application likely limited the potential for NH_3 volatilization loss and subsequently any significant impact on corn grain production. Throughout the four-year study, drainage treatments did not affect ($P \leq 0.05$) NH_3 volatilization loss (data not presented). However, N fertilizer source significantly affected NH_3 volatilization loss in two of four growing seasons (Fig. 4.5 and Table 4.2). In 2010, fertilizer-induced NH_3 volatilization loss was 18.23 kg NH_3-N ha^{-1}, which represented 7.8% fertilizer N loss. That year, polymer-coated urea significantly ($P \leq 0.05$) reduced volatilization loss by 79% and limited applied fertilizer loss to 1.6%. Also in 2010, ammonia volatilization loss was significantly ($P \leq 0.05$) greater than in all other growing seasons (data not presented). Presumably, this was due to the delayed N application until June 25 and limited rainfall after application, which resulted in the greatest amount of fertilizer-induced NH_3

volatilization loss. In 2011-2013, NH_3 volatilization loss was minimal due to rainfall that occurred within 24 hrs after applying N. The percent loss of fertilizer applied during these growing seasons (2011-2013) was less than 2%. This parallels findings of other studies that rainfall or irrigation occurring within 24 hrs of applying N effectively mitigated the potential for substantial NH_3 volatilization loss by moving urea-N deeper into the soil profile and so reduced its potential for volatilization loss (Holcomb III et al., 2011; Jantalia et al., 2012; Sharpe et al., 2004). Although it may be of limited agronomic significance, fertilizer-induced NH_3 loss in 2013 was reduced significantly from 3.24 kg NH_3-N ha^{-1} with NCU to 1.36 kg NH_3-N ha^{-1} with PCU, which represented a 58% reduction. In all four growing seasons, volatilization loss stabilized by 17 days after N application. The short period in which NH_3 volatilization occurred in the study was similar to what has been observed elsewhere (Al-Kanani et al., 1991; Holcomb III et al., 2011; Ma et al., 2010; Sharpe et al., 2004).

When fertilizer-induced NH_3 volatilization was totaled over the four growing seasons, PCU reduced loss by 73% compared to NCU (Table 4.2). The reduction in NH_3 volatilization over the four years with PCU compared to NCU was similar to Xu et al. (2013) who reported a 72% reduction in NH_3 volatilization loss in a double-crop rice production system with PCU compared to NCU. However, the opposite response was observed in an irrigated corn production study where surface-broadcasted N fertilizer had a 65% increase in NH_3 volatilization loss with PCU compared to NCU (Jantalia et al., 2012). These studies' contrasting NH_3 volatilization loss potentials of PCU and NCU may indicate the importance of incorporating PCU into the soil. The polymer-coating of urea prills with PCU possibly prevented the transport of urea-N with water into the soil profile where the potential for volatilization loss is significantly lower. Therefore, volatilization loss potential with PCU might be greater in comparison to NCU in the absence of incorporation.

When averaged over four growing seasons, the percent fertilizer loss from NH_3 volatilization ranged from 0.8 with PCU to 2.8% with NCU (Table 4.2). This represented a significant ($P \leq 0.05$) reduction in fertilizer N loss from NH_3 volatilization with PCU compared to NCU. The relatively low percentage of fertilizer N loss from volatilization observed in this study for both NCU and PCU presumably was due to the incorporation of urea fertilizers directly after application, as well as the occurrence of rainfall in three of the four growing seasons. This result is in accordance with studies showing that incorporating N fertilizer into the soil profile, whether with water movement, tillage, or mechanical placement, can reduce NH_3 volatilization to negligible levels (Holcomb III et al., 2011; Nathan and Malzer, 1994; Rochette et al., 2013).

CONCLUSIONS

The use of subsurface tile drainage did not affect gaseous N loss (N_2O and NH_3) from a claypan soil. Controlled-release PCU broadcast-applied and incorporated reduced soil N_2O emissions 47% and NH_3 volatilization loss 73% compared to NCU in a claypan soil over dry and wet growing seasons. Increased yield production and reduced soil N_2O emissions with PCU compared to NCU resulted in a 53% reduction of yield-scaled emissions of N_2O. The environmental benefits of PCU are derived from the controlled-release properties, which lower the potential for gaseous N loss during the period of greatest risk for gaseous loss. Due to typically wet field conditions during this study in a claypan soil, applied and incorporated N fertilizer loss with NH_3 volatilization did not exceed 2% when applied before a rainfall. Soil N_2O emissions over wet and dry growing seasons ranged from 2 to 4% of applied N. Poor internal drainage associated with claypan soils and high rainfall in spring resulted in a large potential for denitrification loss and subsequent soil N_2O emissions. Greater soil N_2O emissions from claypan soils than is commonly observed in other soils illustrates the importance of reducing gaseous emissions through the use of enhanced-efficiency fertilizers, such as PCU.

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Table 4.1. Select soil chemical properties from fall soil sampling at depths of 0 to 0.3, 0.3 to 0.6, and 0.6 to 0.9 m in 2010, 2011, 2012, and 2013. Data were averaged over tile drainage systems and N fertilizer sources.

Year	Depth	pH	Organic matter	Neut.† acidity	CEC	Bray I P	Exchangeable (1 M NH_4AOc) Ca	Exchangeable (1 M NH_4AOc) K	Exchangeable (1 M NH_4AOc) Mg	NH_4^+-N‡	NO_3^--N
	m	0.01 M $CaCl_2$	g kg^{-1}	--$cmol_c$ kg^{-1} --		mg kg^{-1}	-------------------kg ha^{-1}---------------------				
2010	0-0.3	5.7	24	1.7	18.8	40.0	6334	519	626	12.8	21.2
	0.3-0.6	5.0	19	5.9	29.5	10.9	7696	461	1604	------	------
	0.6-0.9	4.9	12	5.1	29.3	15.0	7501	435	1866	------	------
2011	0-0.3	6.4	27	1.1	16.3	34.2	5580	512	583	24.6	10.1
	0.3-0.6	5.2	22	5.8	26.7	11.3	6851	607	1332	28.7	6.7
	0.6-0.9	5.2	14	4.0	23.6	17.9	6200	533	1409	23.4	2.8
2012	0-0.3	6.1	22	1.7	15.9	40.5	5156	462	575	15.6	98.5
	0.3-0.6	5.2	17	5.3	23.9	13.6	6183	375	1180	18.3	35.1
	0.6-0.9	5.0	10	4.8	23.9	16.6	6084	345	1398	17.4	11.7
2013	0-0.3	5.8	21	2.4	17.1	34.2	5341	479	607	24.5	82.4
	0.3-0.6	5.1	16	6.1	25.9	9.7	6537	405	1271	29.8	65.4
	0.6-0.9	5.0	9	4.9	26.6	21.4	6971	433	1526	28.1	28.0

† Abbreviations: CEC = cation exchange capacity; Neut. = neutralizable.
‡ NH_4^+-N and NO_3^--N were not analyzed at the depths of 0.3-0.6 and 0.6-0.9 m in 2010.

Table 4.2. Fertilizer-induced and applied fertilizer loss from ammonia volatilization for polymer-coated urea (PCU) and non-coated urea (NCU) by growing season and totaled over four seasons.

Year†	N source‡			
	NCU	PCU	NCU	PCU
	Fertilizer induced NH_3 loss§		Applied fertilizer loss as NH_3	
	------- kg NH_3-N ha^{-1} --------		-------------- % --------------	
2010	18.23a	3.84b	7.79a	1.64b
2011	1.26a	0.50a	0.62a	0.25a
2012	0.55a	0.87a	0.27a	0.43a
2013	3.24a	1.36b	1.60a	0.67b
Total	23.28a	6.57b	2.77a	0.78b

† Yearly fertilizer induced ammonia volatilization loss was summed over the first 42 days after N fertilization.

‡ Letters following N sources indicate least significant differences ($P \leq 0.05$) in fertilizer induced and applied fertilizer loss among treatments within each year and totaled over the four year study. Comparisons between columns are not valid.

§ Fertilizer induced NH_3 loss was calculated by subtracting the NH_3 loss from the non-drained, non-fertilized control.

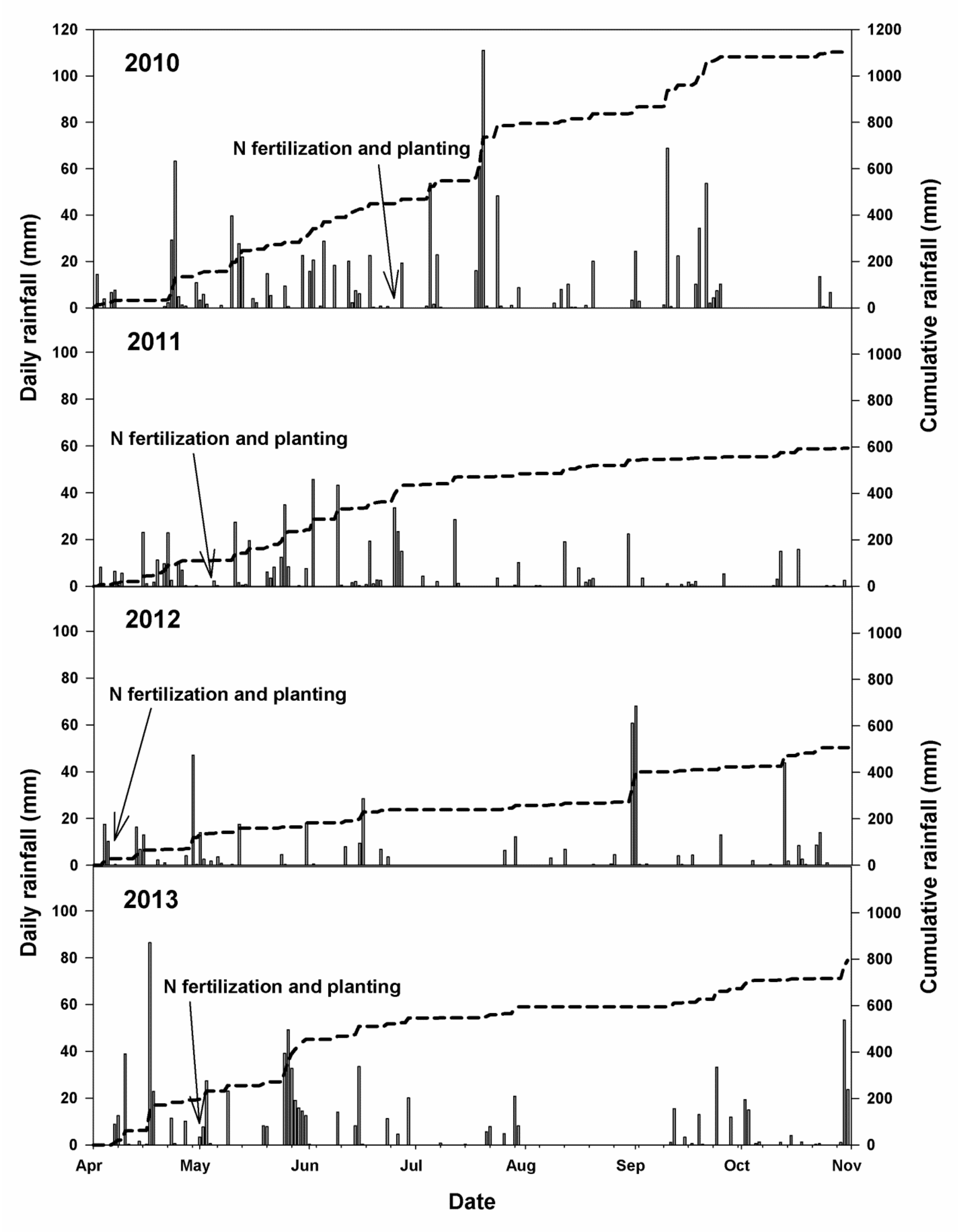

Figure 4.1. Daily (bars) and cumulative (lines) rainfall from April through October at the University of Missouri, Greenley Memorial Research Center from 2010-2013.

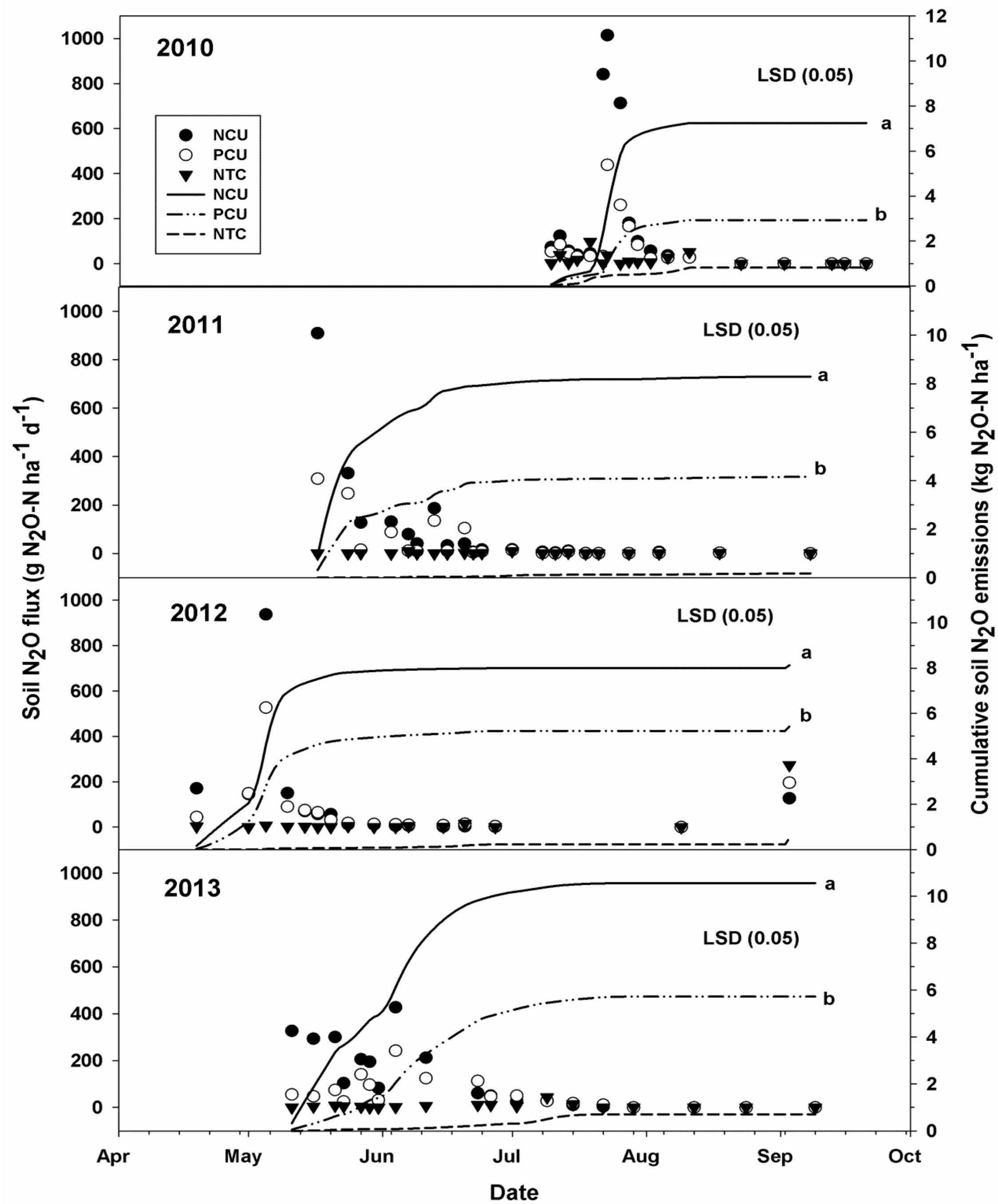

Figure 4.2. Nitrogen fertilizer source (non-coated urea = NCU, polymer-coated urea = PCU, non-treated control = NTC) effects on soil N_2O flux and cumulative emissions over the 2010-2013 growing seasons. Data were averaged over drainage treatments. Letters following fertilizer treatments represent differences in cumulative soil N_2O emissions by year using Fisher's Protected LSD ($P \leq 0.05$). The NTC treatment was not included in the statistical analysis, but it was included as a baseline reference.

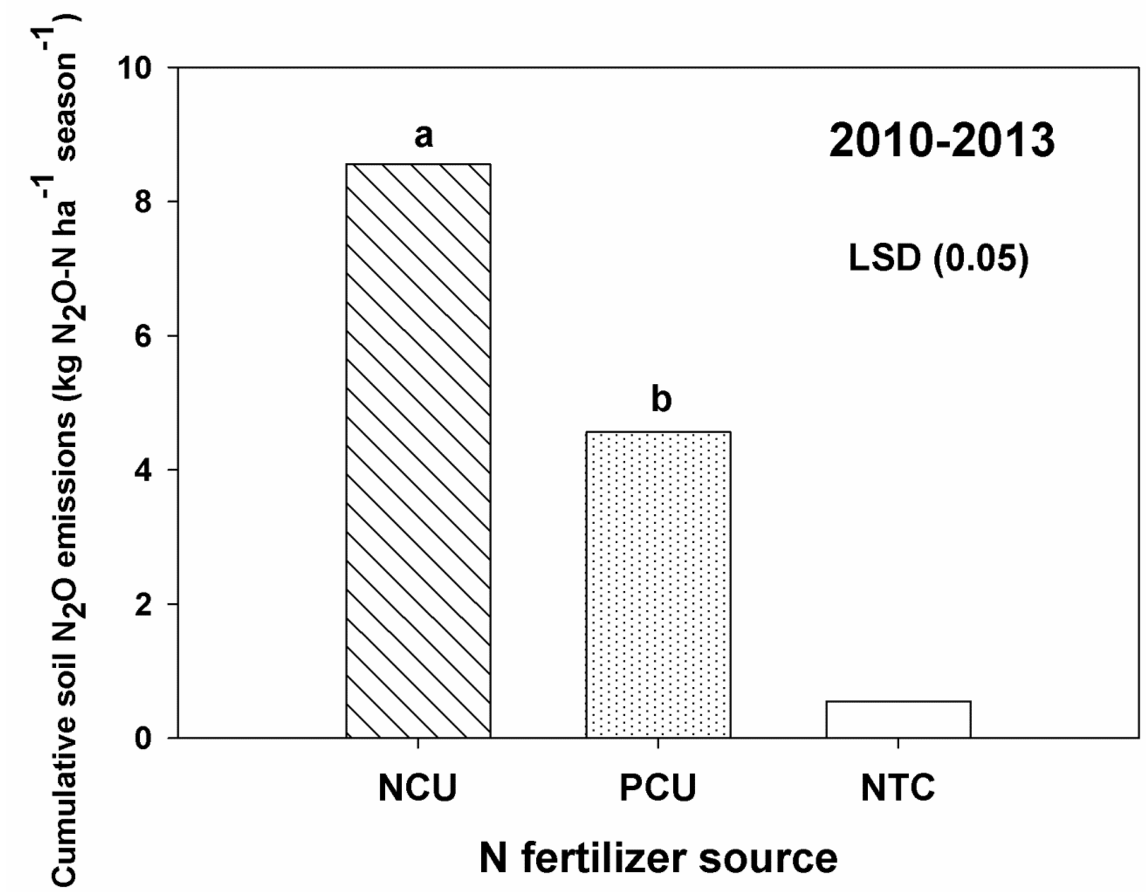

Figure 4.3. Cumulative soil N_2O emissions by N fertilizer source (non-coated urea = NCU, polymer-coated urea = PCU, non-treated control = NTC) averaged over drainage treatments and years. Letters following fertilizer treatments represent differences in cumulative soil N_2O emissions using Fisher's Protected LSD ($P \leq 0.05$). The NTC treatment was not included in the statistical analysis, but it was included as a baseline reference.

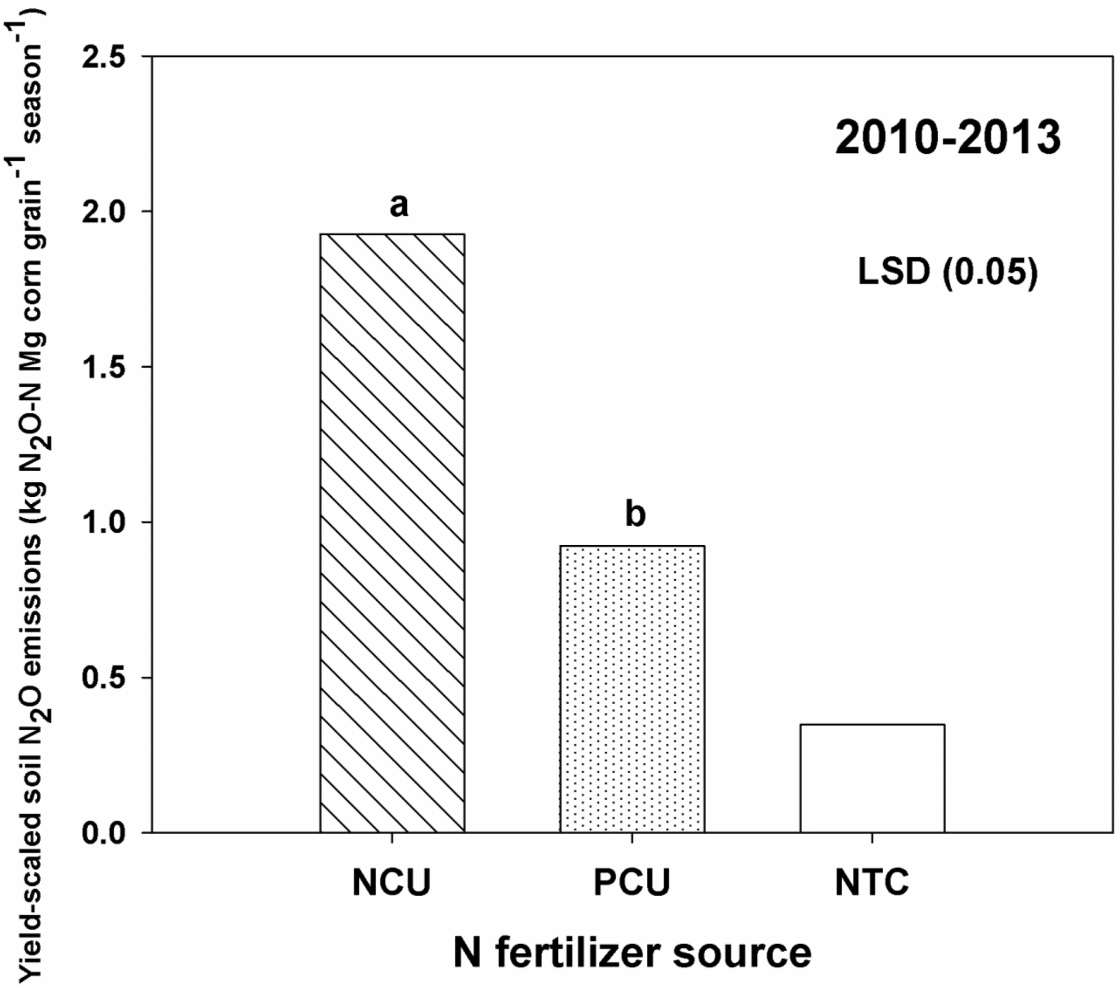

Figure 4.4. Yield-scaled soil N_2O emissions by N fertilizer source (non-coated urea = NCU, polymer-coated urea = PCU, non-treated control = NTC) averaged over drainage treatments and years. Letters following fertilizer treatments represent differences in yield-scaled soil N_2O emissions using Fisher's Protected LSD ($P \leq 0.05$). The NTC treatment was not included in the statistical analysis, but it was included as a baseline reference.

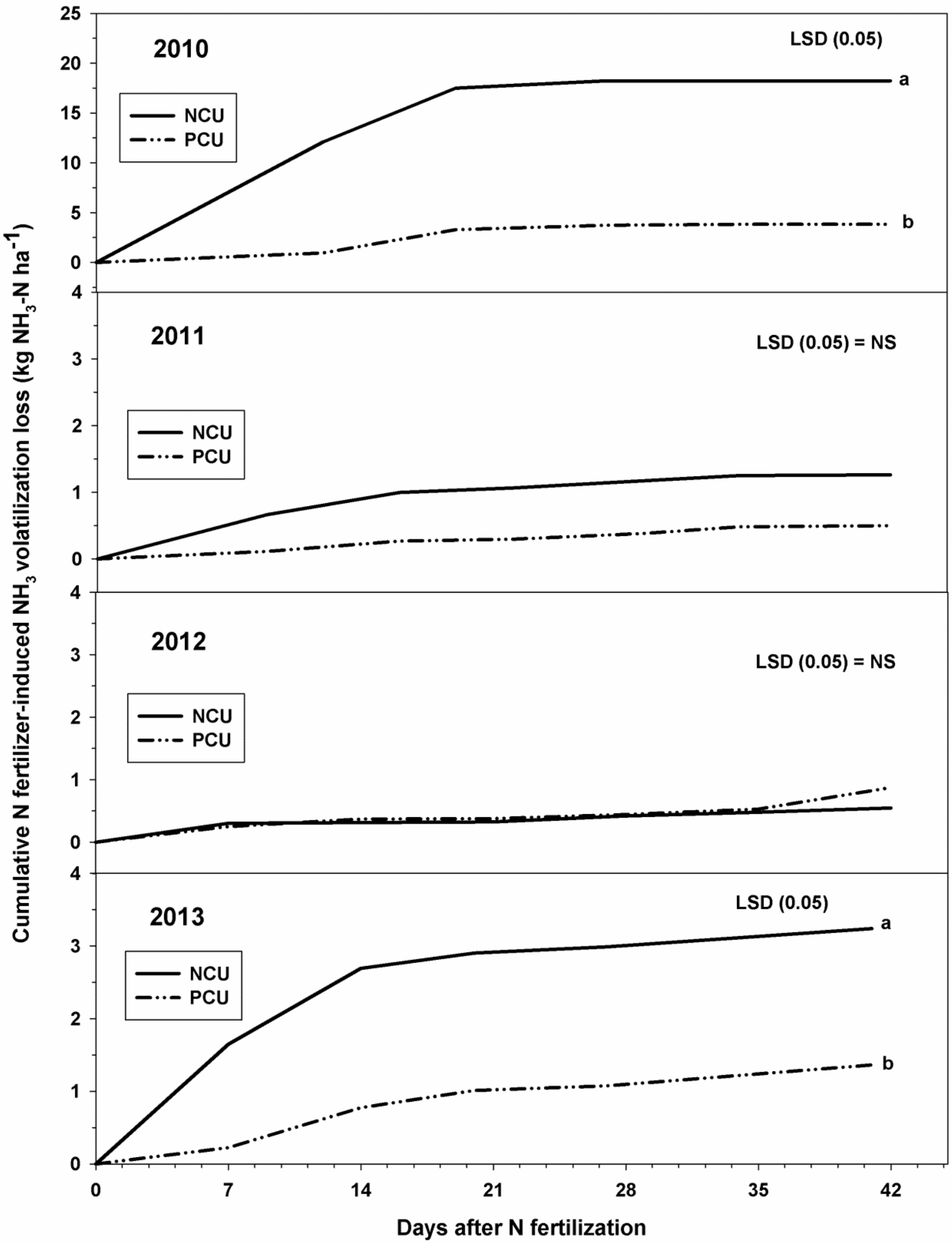

Figure 4.5. Cumulative N fertilizer-induced NH_3 volatilization loss over 42 days after surface broadcast application and incorporation in each growing season. Nitrogen fertilizer sources were averaged over drainage treatments. Letters following cumulative volatilization loss from N sources represent significant ($P \leq 0.05$) differences within years using Fisher's Protected LSD.

CHAPTER 5

CORN YIELD RESPONSE TO MANAGED DRAINAGE AND POLYMER-COATED UREA FERTILIZER IN A POORLY-DRAINED, RIVER BOTTOM SOIL

ABSTRACT

Wabash silty clay soils located in Missouri river bottoms have not traditionally been tile drained due to high clay content in the surface soil layers and low overall soil hydraulic conductivity. A combination of increased land and corn (*Zea mays* L.) grain prices and increased variability and intensity of rainfall among and within growing seasons have stimulated interest in the region to utilize managed subsurface drainage (MD) to increase corn yields. The objective of the study was to determine the effect of subsurface tile drainage systems [no drainage (ND), free drainage (FD), and MD] and N fertilizer source [polymer-coated urea (PCU) or non-coated urea (NCU] management on corn grain yield in a poorly-drained river bottom soil. Applications of PCU did not impact corn yield regardless of the presence or absence of drainage. Averaged over 2011 and 2012, drainage (FD or MD) increased corn yield by 9% compared to ND. Increased corn yield with MD compared to FD was not observed over the three year study. Increased yields in the poorly-drained, bottomland soil with the presence of subsurface tile drainage was possibly due to from greater root development in the spring and improved water use efficiency during the dry summer months compared to ND.

INTRODUCTION

Poorly-drained river bottom soils can produce high corn grain yields; however, saturated soil conditions and flooding often limit production. Wabash silty clay soils have not traditionally been tile drained due to high clay content in the surface soil layers and low overall soil hydraulic conductivity (Miller et al., 1914; Watson, 1979) which required narrow tile spacing and made installing tile drainage less economically viable. The combination of increased land and corn grain prices (University of Missouri, 2009) and increased intensity and variability in rainfall among and within growing seasons has stimulated an interest in installing subsurface tile drainage systems in river bottom soils.

For most poorly-drained soils, free subsurface drainage (FD) often results in increased corn yields compared to no drainage (ND) (Fausey, 1983; Kladivko et al., 2005; Nelson and Motavalli, 2013). Many studies involving tile drainage have been conducted on fields that have been uniformly tile drained at spacings required to adequately drain the entire field, and, therefore, did not have a ND comparison. Those type of tile drainage studies have focused on the impact of management practices such as N application timing (Randall and Vetsch, 2005) and tillage (Vetsch et al., 2007) on corn yield. Extensive research involving corn production and tile drainage has focused on reducing N leaching loss in tile drainage water (Kladivko, et al., 1991; Randall et al., 2000; Strock et al., 2004; Qi et al., 2011) due to high N fertilizer inputs required to maximize corn yields (Adviento-Borbe et al., 2010) and the environmental concern over nitrate in tile drainage water (USEPA, 1992).

Research evaluating the difference in corn yield among FD and ND has been limited to soil types not traditionally tiled drained, such as a poorly-drained, river bottoms with high clay content. Kladivko et al. (2005) reported that a poorly-drained, Clermont soil in Southern Indiana, FD (5 m spacing) over ten years increased corn yield 7% compared to ND. Six years of research conducted on a claypan soil in Northeast Missouri reported increased corn yield (13-82%) with FD (6.1 m spacing) compared to

ND (Nelson et al., 2009; Nelson and Smoot, 2012; Nelson and Motavalli, 2013). A unique trend from the tile drainage studies on claypan soils was increased yield with FD compared to ND across wet and dry growing seasons. Cool, wet spring and dry, warm summer months typical of the central Midwest region of the U.S. in combination with early planting dates (Norwood and Currie, 1996; Kucharik, 2008; Van Roekel and Coulter, 2011), increased root development (Eghball and Maranville, 1993), and increased water use efficiency during the dry summer months (Lorens et al., 1987; Skinner, 2008) may explain why FD increased corn yield compared to ND in relatively dry growing seasons.

Recent advances in subsurface drainage technology allow for the management of the water table height with the addition of a water level control structure to tile drainage systems, which is commonly referred to as a controlled or managed subsurface drainage system (MD) (Brown et al., 1997). During dry periods in a cropping season, MD has been reported to increase retention of crop-available water and crop nutrients in the root zone (Wesström and Messing, 2007), which may lead to increased yield with MD compared to FD. A two-year research study conducted in Canada reported increased corn yield (1-5%) in each season with MD compared to FD (Drury et al., 2009). Delbecq et al. (2012) reported increased corn yield (5.8-9.8%) with MD compared to FD over a five-year study. However, extensive research has yet to be conducted to determine if MD can consistently increase corn yield compared to FD in the Midwestern U.S.

Polymer-coated urea (PCU) is a controlled release urea fertilizer that can limit environmental loss of applied N early in the growing season (Nash et al., 2012). Once applied to the soil, the rate of urea-N release out of the polymer-coating was controlled by temperature and moisture (Fujinuma et al., 2009). In Northeast Missouri, the percent release of urea from PCU applied in April can be less than 40% by June (Nash et al., 2012; Nelson et al., 2014). Wet soil environments with high potential for early season loss of applied N increased apparent N recovery efficiency and corn yields with PCU compared to traditional non-coated urea (NCU) fertilizer (Noellsch, 2009).

High amounts of rainfall are typically observed from March to April in Northeast Missouri. Combining PCU with MD to mitigate early season N loss and conserve water during the dry summer period could further maximize corn production. Polymer-coated urea could minimize N leaching through drainage systems, but few research studies have evaluated corn yield response to PCU in combination with MD or FD. Nelson and Motavalli (2013) reported PCU increased corn yield 7% compared to NCU with FD (12.2 m spacing). However, Nelson et al. (2009) found reduced corn yield (6%) with PCU compared to NCU with FD in an extremely dry year. Further research is needed to determine if the addition of PCU with tile drainage can increase corn production. The poorly-drained Wabash soil series, representative of higher clay soils in in river bottoms of Northeast Missouri, has not been extensively tile drained. The objective of this research was to determine corn yield response to MD and PCU compared to ND and NCU in a leveed river bottom soil.

MATERIALS AND METHODS

Site Description and Experimental Design

A four year study located on a private farm production field in Northeast Missouri (40^{o}3’11.5” N, 92^{o}4’ 21.2”W) with a poorly-drained, river bottom soil was initiated in April 2010 and ended in November 2013. The soil type was Wabash silty clay (fine, smectitic, mesic Cumulic Vertic Endoaquolls). Subsurface tile drainage was installed in August 2009 at a depth of 0.9 m with 6.1 m spacing. Soil samples were collected from all plots at three depths (0.3, 0.6, 0.9 m) with a Giddings probe (Giddings Machine Company, Windsor, CO) following harvest in all years. Soil properties obtained from the analysis of those samples followed standard soil testing analytical procedures for Missouri (Nathen et al., 2006). Soil NH_4^+-N and NO_3^-N concentrations were converted from mg kg^{-1} to kg ha^{-1} based on soil bulk density measurements taken at the depths of 0-0.3, 0.3-0.6, and 0.6-0.9 m at the field site in 2013. Soil properties were averaged over years (2011-2013) and presented by year at each depth (Table 5.1). Soil nitrate-N concentration after harvest in the fall was high in 2012 and 2013, which was probably due to drought conditions which limited plant N uptake and N loss. Daily rainfall was measured on-site using an automated rain gauge and datalogger (Automata, Nevada City, CA) (Fig. 5.1). Historical rainfall data for the region was obtained from an automated weather station (Campbell Scientific, Inc., Logan, UT) located at the Greenley Memorial Research Center, approximately 24 km southwest of the field site.

The field site was in continuous corn production in conjunction with tillage occurring directly prior to planting (Sunflower disk harrow, Beloit, KS) and deep tillage (Blu-Jet, SubTiller 4, Thurston Manufacturing Company, Thurston, NE) after harvest for residue management. Corn stubble that remained following the 2012 harvest was burned directly prior to tillage. Corn was planted in 76-cm-wide rows at 79,000 seeds ha^{-1} on 9 May 2011, 15 May 2012, and 14 June 2013. The 2010 study year was excluded from the study due to a flooding event that resulted in a complete crop failure due to excessive surface water and the lack of a functional outlet when the river was high. Corn hybrid

‘Pioneer 1018’ was planted in 2010-2012, and ‘Pioneer 1498’ was planted in 2013. Management decisions, such as planting and harvest date, were made by the collaborating farmer.

The experiment was arranged in a randomized complete block design with two replications. Drainage treatments included a ND, FD, and MD (water table control structure, Agri Drain Corporation, Adair, IA) (Fig. 5.2). Nitrogen fertilizer sources included NCU or PCU (ESN, Agrium Advanced Technology, Denver, CO) which were broadcast-applied annually prior to planting at 202 kg-N ha^{-1} and incorporated into the soil (5-10 cm) with a disk-harrow (Sunflower, Beloit, KS) within 24 hours of application. This N application rate was based on a typical application rate for corn grain production in this region. Management decisions regarding when to put MD into free or managed drainage mode were made based on soil moisture conditions and the need to either drain or conserve soil water in order to maximize corn production (Fig. 5.2).

The same field plots were used each year and the N fertilizer treatments were repeated each year throughout the four years of this experiment. Plots were 18 by 366 meters long. An additional three meters were added to the sides of each plot to negate any potential movement of N fertilizer into adjacent plots. Corn grain yields (adjusted to 150 g kg^{-1} moisture) were calculated from a yield monitor (Greenstar 2, John Deere, Moline, IL). The width used to calculate yields were the center eight corn rows in plots that spanned the width of the tile drains, while in regard to plot length, the top and bottom third of the field site was excluded from the calculation of yields due to non-uniformity. Corn grain samples were collected annually from each plot during harvest were analyzed for protein and moisture with a Foss Infratec 1241 (Eden Prairie, MN). Annual collection of whole corn plant samples at physiological maturity were taken directly over a tile drain (1.5 m) and between the tile drains (1.5 m) in each plot and were weighed, ground, dried, and used to estimate silage yield. Whole corn plant samples were then analyzed for total N and total C concentration and combined with silage yield to estimate N and C uptake.

Statistical Analysis

A two-way factorial, randomized complete block ANOVA was used to determine significant differences among treatments with corn grain yield, protein, and moisture, as well as whole plant silage, N uptake, and C uptake at physiological maturity. The interaction of drainage and N source did not result in a significant ($P \leq 0.10$) response in any corn production measurement. Nitrogen fertilizer source did not significantly ($P \leq 0.10$) affect corn grain yield throughout the study. Corn yields were averaged over the N fertilizer source main effect and presented by year. Corn grain protein and moisture concentration, and whole plant silage, N uptake, and C uptake at physiological maturity were not found to have a year interaction; therefore, data were pooled over years and analyzed by drainage and N fertilizer source main effects. The statistical program, SAS v9.3, with PROC GLM was used for ANOVA and Fisher's Protected LSD was used to separate means and determine significant treatment effects (SAS Institute, 2013).

RESULTS AND DISCUSSION

Rainfall and Flood Events

A severe flash flood in June 2010 led to a total corn crop failure; therefore, 2010 data were not presented. Due to the landscape position of river bottom soils, flood events can extend saturated soil conditions for longer periods, which back up the tile outlets and restrict water drainage from the soil through the tile drains. In 2011, a 1.5 m pump was installed by the cooperator to remove surface water and allow water flow from the tile drainage outlet.

Total rainfall from March through November was similar in 2011 and 2013 (820 to 856 mm), while 2012 was drier (516 mm) (Fig. 5.2). The 11-yr average (2000-2010) of total rainfall over the period of March through November was 893 mm (data not presented). Total rainfall in 2011 and 2013 was similar to the 11-yr average, while 2012 was historically dry. In the Corn Belt of the Midwest, cool temperatures, high rainfall, and low evapotranspiration rates typically result in wet field conditions in the spring, while warm temperatures, low rainfall, and high evapotranspiration rates are typical of the summer months which result in dry field conditions (Mclsaac et al., 2010; Yeh et al., 1998). Therefore, rainfall distribution during a growing season can have a large impact on grain yields.

Rainfall distribution in 2011-2013 varied considerably from the 11-yr average. In 2011, total rainfall in the spring (March-May), summer (June-August), and fall (September-November) was -18, -17, and +18% of the 11-yr average, respectively. Although rainfall was below the 11-yr average in the summer months, high amounts of rainfall were received over a two-day period which led to a flash flood that persisted for approximately two days. The lift station prevented a crop failure from occurring in 2011. However, slight lodging of the corn plants was observed between the borders (12.2 m spacing) of the drain tiles, while less lodging was observed between the drain tiles (6.1 m spacing) after the flood event ceased. In 2012, total rainfall in the spring, summer, and fall was -27, -59, and -36% of the 11-yr average, respectively. Total rainfall in the spring, summer, and fall of 2013 was +60, -61, and -1% of the 11-yr average, respectively. High rainfall in late May occurred directly after N application and incorporation led to a significant flood event that persisted for approximately five days and delayed planting until June 14. Additionally, flooding of the field site commonly occurred during the non-cropping period over 2011-2013 (data not presented).

Corn Grain Yield

Corn grain yields and response to drainage varied among the 2011, 2012, and 2013 growing seasons (Table 5.2). Nitrogen fertilizer source did not affect corn grain yields in 2011-2013 regardless of drainage (data not presented). Lack of a corn yield response to N fertilizer source through the study was likely due to drought conditions, limited plant N uptake, and N loss which resulted in carry-over N among seasons (Table 5.1). Additionally, lack of a corn grain yield response to PCU with FD or MD in 2011-2013 may indicate that the narrow drainage spacing was able to effectively mitigate extended periods of saturation that have shown to enhance the potential for increased corn yield with PCU compared to NCU (Noellsch et al., 2009). However, PCU may reduce N leaching in tile drained fields (Chapter 3 and 6). Corn yield response to PCU compared to NCU with tile drainage has been observed in other research studies due to tile spacings. Non-coated urea increased corn yield 3% at a 6.1 m tile spacing compared to PCU; however, PCU increased corn yield 7% compared to NCU at 12.2 m tile spacing (Nelson and Motavalli, 2013).

The 2011 study year was unique due to a total corn crop failure in 2010 that resulted from extensive surface water runoff into this leveed field. In the absence of a lift station to remove water and allow the tile outlet to function, the entire corn field was lost in 2010. Corn grain yields in 2011, averaged over N source, only differed by 0.1 Mg ha^{-1}

(Table 5.2). Evaluation of the amount of ammonium and nitrate in the soil (0-0.91 m depth) directly after harvest revealed 144 and 23% greater ammonium and nitrate in 2010 than in 2011, respectively (data not presented). This result indicated that significant carry-over of N fertilizer from 2010 into 2011 may have occurred. High soil N availability in combination with relatively dry conditions in the spring and early summer months of 2011 may have masked the corn yield response to drainage and N source, as well as any N loss differences among N source.

Both 2012 and 2013 experienced drought conditions that persisted over the entire summer months (Fig. 5.2). This low moisture condition probably led to low overall yields in 2012 and 2013 (Table 5.2). Water stress during the reproductive growth stages of corn has been shown to dramatically lower corn yields (Grant et al., 1989; Bai et al., 2006). Corn grain yields in 2012 were 5.8, 6.5, and 6.6 Mg ha^{-1} with ND, FD, and MD, respectively. The presence of drainage (FD or MD) in 2012 increased yield by 13% compared to ND. In 2013, although not statistically significant ($P \leq 0.10$), drainage systems (FD or MD) averaged 7% greater corn grain yield than ND. The percent yield increase with the presence of drainage compared to ND was similar to the 7% increase reported over multiple years in a non-traditionally tile drained Clermont silt loam soil in Ohio and Indiana (Fausey et al., 1983; Kladivko et al. 2005).

Previous tile drainage research in the Midwest has found that subsurface drainage can allow for earlier planting compared to non-drained soils (Kladivko et al. 2005; Nelson and Motavalli, 2013). Corn planting dates have shifted to earlier dates in states that generally have extensive subsurface drainage (Kucharik, 2008). Early planting with the addition of drainage could affect yield potential in river bottom soils as long as an adequate outlet is available to reduce the flood risk.

Increased corn yield with drainage (FD or MD) compared to ND in years that had rainfall that was below average was likely a function of landscape position and increased root development. Low landscape position of river bottom soils, cool temperatures, and low evapotranspiration rates (Yeh et al., 1998) typically result in wet field conditions for an extended period of time after corn emergence regardless of whether high amounts of rainfall were received. Research has shown that inducing mild water stress early in a growing season was beneficial to plant development by stimulating greater root development (Eghball and Maranville, 1993). This greater root volume allowed the plant to maintain plant-soil water potentials leading to greater water use efficiency during dry summer months, as compared to a shallower, less robust root system (Lorens et al., 1987; Skinner, 2008). We speculate that lower soil moisture and increased aeration of these poorly-drained soils in the spring period with drainage increased root development compared to ND, which in combination with dry summer conditions resulted in greater corn grain yield production with drainage (FD or MD) compared to ND. Additionally, the inherently wet nature of poorly-drained river bottom clayey soils in the central Midwest during the spring may allow for tile drainage to maintain increased corn yield over ND across varying growing season conditions.

Although research is limited, MD has been shown to increase corn yield up to 9.8% compared to FD in clayey soils in Canada (Drury et al., 2009; Delbecq et al., 2012). This response was presumably a function of the ability to restrict tile drainage flow with MD, which conserved plant available water into the drier summer months. Managed subsurface drainage did not increase corn grain yield compared to FD any of the three study years. This was likely due to flash drought events that extended throughout the summer months in two of the three study years. Farmers in this region may wish to be proactive in water table management with MD in order to obtain the potential yield benefits with MD over FD.

Corn Nitrogen Uptake

Whole plant uptake of N at physiological maturity was significantly (*P* = 0.04) affected by drainage (Table 5.3). Averaged over 2011-2013, whole plant N uptake ranged from 141 to 175 kg-N ha^{-1}. Corn N uptake was significantly greater (19%) with ND compared to MD. This was counter to other research indicating that improved plant growth conditions with the presence of drainage typically increased corn N uptake compared to ND (Nelson et al., 2009; Nelson and Motavalli, 2013). There was no significant (*P* = 0.15) N source effect on corn N uptake (Table 5.2). However, averaged over 2011-2013, corn N uptake was 8% greater with NCU compared to PCU. Lower corn N uptake with PCU compared to NCU was observed in drainage research on a claypan soil in Northeast Missouri, during a season with adequate rainfall distributed over the growing season (Nelson, et al., 2009). However, Nelson et al. (2009) reported greater corn N uptake with PCU compared to NCU during a drought year that was similar to 2012 and 2013. Contrasting responses of corn N uptake to PCU and NCU over different growing season conditions may be due to soil type, landscape position, and spring rainfall conditions that may affect loss of N.

Carbon Uptake and Silage

Whole corn plant C uptake was significantly affected by the main effect of drainage (*P* = 0.05) and N source (*P* = 0.02) (Table 5.3). Averaged over 2011-2013, corn C uptake was 7.5 Mg C ha^{-1} for FD or MD, and 8.0 Mg-C ha^{-1} with ND. Carbon uptake was 6% greater with ND compared to FD or MD. Similar to corn N uptake, NCU had 6% greater corn C uptake compared to PCU. Corn silage response due to the main effects of drainage and N source was similar to corn uptake of N and C (Table 5.3). Averaged over 2011-2013, ND had 7% greater silage production compared to MD and FD, which probably resulted in greater overall N and C uptake. Non-coated urea averaged 6% greater silage than PCU over 2011-2013.

CONCLUSIONS

The addition of tile drainage in a river bottom soil in Northeast Missouri increased corn grain yields 7 to 13% compared to the absence of drainage. Polymer-coated urea did not show a yield advantage over NCU during this research which was probably due to carry-over N in 2011 and extremely dry conditions in 2012 and 2013. Managed drainage was not found to increase corn yield compared to FD in extremely dry years (2012 and 2013). Farmers in this region may wish to be proactive with the management of drainage flow with MD in order to obtain increased corn yield compared to FD. The inherently wet nature of bottomland soils, may have also allowed increased yield production with tile drainage compared to ND during years that received relatively low rainfall throughout the growing season, such as 2012. However, the potential for flooding was always present during the spring months with the river bottom field and a functional outlet is necessary for subsurface drainage to be successful. Flood events that persist over an extended period of time that back up the tile outlet may nullify any potential for increased corn yield with drainage compared to ND.

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Table 5.1. Select soil chemical properties from fall soil sampling at depths of 0 to 0.3, 0.3 to 0.6, and 0.6 to 0.9 m in 2010, 2011, 2012, and 2013. Data were averaged over tile drainage systems and N fertilizer sources.

							Exchangeable (1 M NH_4AOc)				
Year	Depth	pH	Organic matter	Neut. acidity	CEC†	Bray I P	Ca	K	Mg	NH_4^+-N	NO_3^--N
	m	0.01 M $CaCl_2$	g kg^{-1}	--$cmol_c$ kg^{-1} --		mg kg^{-1}	-------------------kg ha^{-1}				---------------------
2010	0-0.3	5.2	26.4	5.0	27.7	49.7	8370	246	18	18.3	24.8
	0.3-0.6	5.3	18.7	4.0	26.7	14.0	8209	201	14	14.3	11.5
	0.6-0.9	5.6	13.8	2.4	26.2	11.8	8432	217	13	13.2	9.7
2011	0-0.3	5.5	30.7	3.7	25.1	43.7	7708	395	1029	32.9	14.1
	0.3-0.6	6.0	23.8	1.9	26.2	11.9	8530	383	1284	18.2	11.5
	0.6-0.9	6.4	17.8	0.7	24.5	5.6	8290	393	1322	15.6	8.8
2012	0-0.3	5.1	26.2	5.8	25.8	56.7	7263	261	928	16.1	47.7
	0.3-0.6	5.6	20.2	3.5	24.6	10.5	7475	217	1102	5.5	14.1
	0.6-0.9	5.9	14.7	2.1	23.5	5.3	7519	219	1190	5.3	6.7
2013	0-0.3	5.3	27.8	5.7	25.5	55.8	6903	221	1121	11.3	103.2
	0.3-0.6	5.5	23.7	4.6	25.4	12.8	7063	168	1294	6.3	31.3
	0.6-0.9	5.8	16.8	2.6	24.4	8.1	7320	179	1413	4.5	16.7

† Abbreviations: CEC = cation exchange capacity; Neut. = neutralizable.

Table 5.2. Corn grain yield response to drainage treatments by year. Data were averaged over N source.

Year	Drainage[†] ND	FD	MD	LSD (*P=0.10*)[‡]
	------------- $Mg\ ha^{-1}$	-------------	-------------	
2011	12.4	12.4	12.3	NS
2012	5.8	6.5	6.6	0.6
2013	8.4	9.0	8.9	NS

[†] Abbreviations: FD = free drainage; MD = managed drainage; ND = non-drained; NS = No significance.
[‡] Letters following drainage treatments denote significant differences among means.

Table 5.3. Main effect of drainage and N fertilizer source on whole corn plant silage, C uptake, N uptake, and corn grain protein and moisture concentration. Data were averaged over years (2011-2013).

Main effects	Silage Yield	C uptake	N uptake	Corn grain Protein	Moisture
	------- $Mg\ ha^{-1}$	-------	-- $kg\ N\ ha^{-1}$ --	-------- $g\ kg^{-1}$	-------
Drainage[†]					
ND	18.5a	8.0a	175a	89	166
FD	17.2b	7.5b	154ab	88	166
MD	17.2b	7.5b	141b	87	166
P > F	0.03	0.05	0.04	0.48	0.94
LSD	0.05	0.05	0.05	NS	NS
N Source					
NCU	18.2a	7.9a	163	87	168a
PCU	17.1b	7.4b	150	89	165b
P > F	0.02	0.02	0.15	0.10	0.05
LSD	0.05	0.05	NS	NS	0.05

[†] Abbreviations: Conc. = concentration; FD = free drainage; LSD = least significance difference; MD = managed drainage; ND = non-drained.
[‡] Letters following silage, C uptake, N uptake, C conc., and N conc. for the main effect of drainage and N source denote significant difference among treatments.

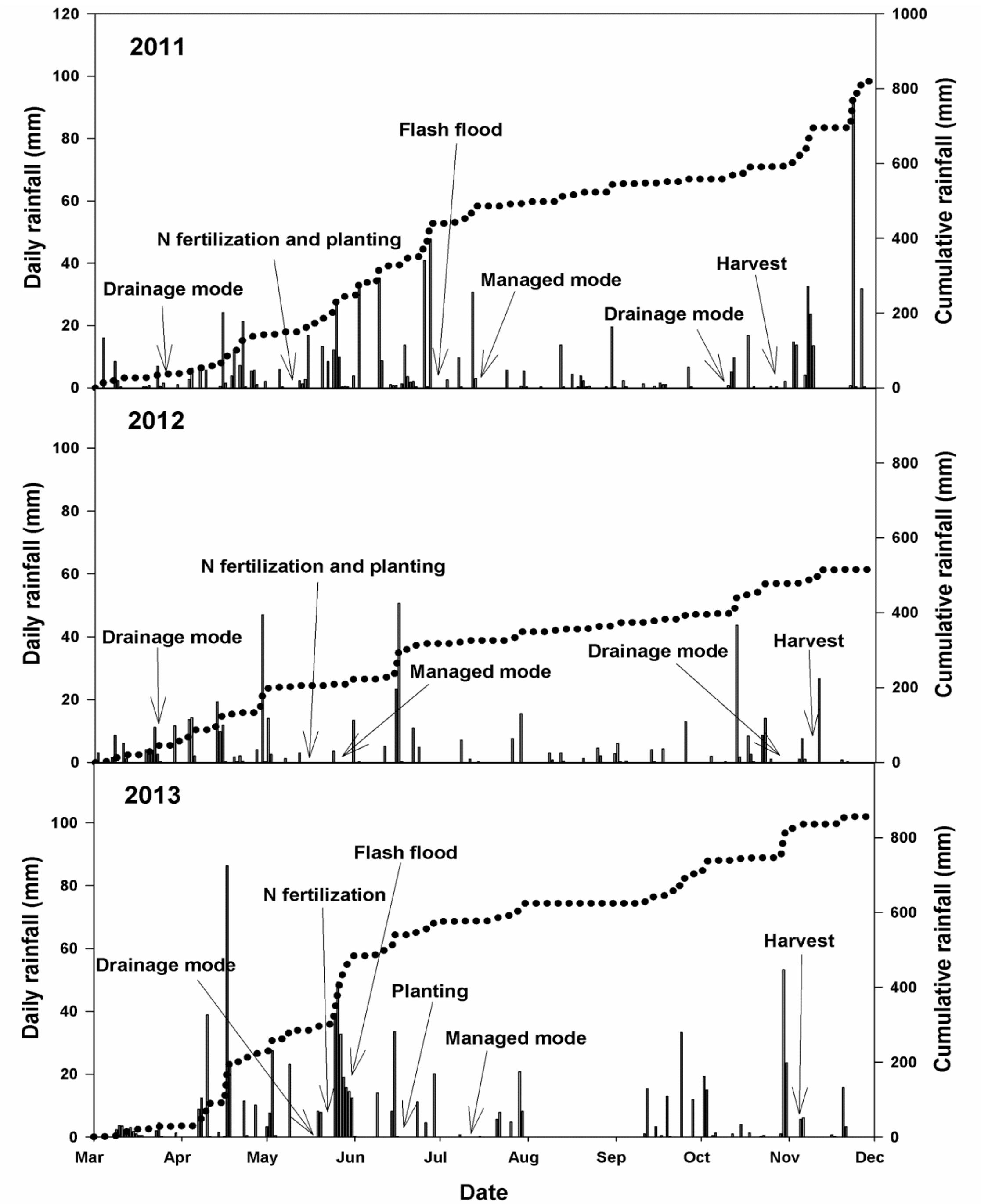

Figure 5.1. Daily (bars) and cumulative (dashed lines) rainfall from March through November at the study site from 2011-2013. Arrows indicate the dates of N fertilization, planting, harvesting, and managing of tile outflow with managed drainage, as well as flash floods that occurred at the study site.

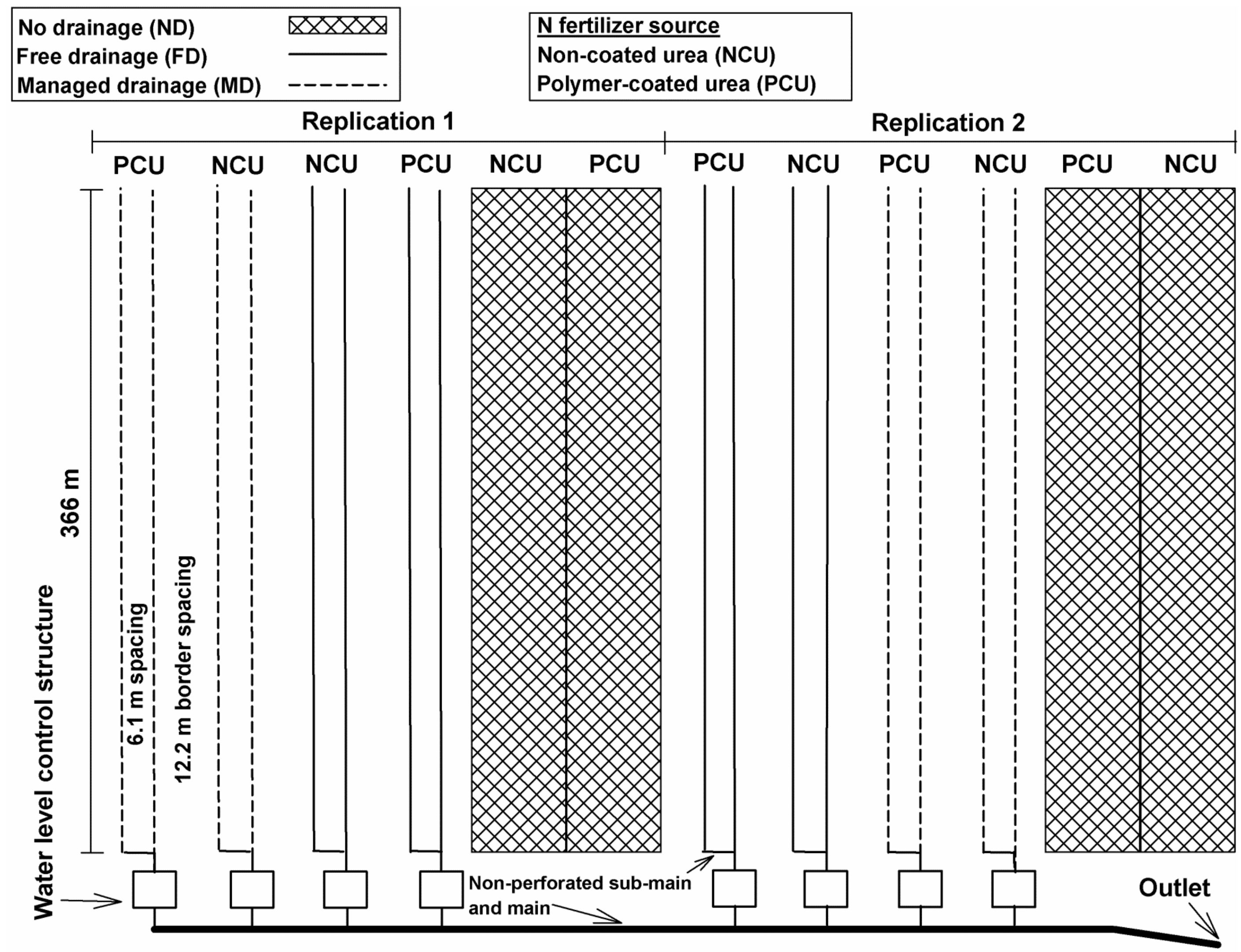

Figure 5.2. Field layout and plot treatments, including the subsurface tile drainage design.

CHAPTER 6

REDUCING NITROGEN LOSS IN TILE DRAINAGE WATER WITH MANAGED DRAINAGE AND POLYMER-COATED UREA IN A SILTY CLAY RIVER BOTTOM SOIL

ABSTRACT

Poorly-drained, river bottom soils can be high corn (*Zea mays* L.) yielding environments, but saturated soil conditions often reduce corn yields. Wabash soils located in river bottoms in Northeast Missouri have not been traditionally tile drained due to high clay content which requires narrow tile drain spacings. Increased land prices in the region have increased interest in tile draining poorly-drained bottom land soils to increase corn yields which could have a deleterious effect on water quality. The objectives of the three-year study were to determine whether use of managed subsurface drainage (MD) in combination with a controlled release N fertilizer could reduce the annual amount of NO_3^--N loss through tile drainage water compared to free subsurface drainage (FD) with a non-coated urea application. Annual NO_3^--N loss through tile drainage water with FD ranged from 28.3 to 90.1 kg N ha^{-1}. Nitrogen fertilizer source did not affect NO_3^--N loss through tile drainage water, which was likely due to limited corn uptake over the three-year study due to adverse weather conditions. Averaged over three years, MD reduced tile water drained 52% and NO_3^--N loss 29% compared to FD. Reduction in NO_3^--N loss through tile drainage water with MD compared to FD was due to reduced tile flow during the non-cropping period. Annual flow-weighted mean concentration of NO_3^--N in the tile water was 5.8 mg N L^{-1} with FD and 8.1 mg N L^{-1} with MD. Tile draining river bottom soils at this location for continuous corn production may not pose a health risk over the evaluated duration.

INTRODUCTION

Poorly-drained, silty clay soils in river bottoms located in Northeast Missouri and throughout the Midwestern U.S. have high soil fertility (Watson, 1979) and can produce high corn yields. However, saturated soil conditions due to poor drainage, high seasonal water tables, and flooding due to the low landscape position often reduce corn yields. Wabash soils have a low overall soil hydraulic conductivity (K_{sat} = 0.01 to 0.10 μm sec^{-1}) due to high clay content throughout the soil profile, which requires narrow subsurface tile drain spacing Therefore, poorly-drained Wabash soils have not traditionally been tile drained as the cost of installing subsurface tile drainage systems are relatively high. Increased land prices in the region (University of Missouri, 2009) and relatively high grain prices may now make tile draining poorly-drained, river bottom soils that have not traditionally been drained an economically viable management option to reduce excessive soil moisture and increase corn yields.

The increased use of free subsurface drainage (FD) in agricultural fields has led to environmental concerns regarding N loading of surface waters (USEPA, 1992). An increased rate of water infiltration and transport out of soils with FD has increased N entering surface waters (Fausey et al., 1995; Gilliam et al., 1999). Aquatic ecosystems can be sensitive to an anthropogenic addition of N as it is one of the most limiting nutrients in aquatic ecosystems. Nitrogen concentrations above natural levels in surface waters can result in hypoxia and eutrophication (USEPA, 1992), which involves rapid algae growth which in turn depletes oxygen levels below what is required for high forms of aquatic life (Burkart and James, 1999). Additionally, nitrate-N concentration above 10 mg N L^{-1} in drinking water has been reported to cause health problems (USEPA, 2009).

The potential for NO_3^--N entering surface waters as a result of agricultural fields with tile drainage is high due to N inputs and the high mobility of NO_3^--N in soil (Sims et al., 1998; Burkart and James, 1999). Additionally, the recent shift toward continuous corn production could further increase NO_3^--N loss in tile drainage water as higher annual rates of N are required to obtain maximum yield compared to crop rotations with soybean, small grains, or forage grasses (Adviento-Borbe et al., 2010). A three-year continuous corn study with N applied at 224 kg N ha^{-1} annually, reported NO_3^--N loss through tile drainage water as high as 59 kg N ha^{-1} annually (Gast et al., 1978). Annual flow-weighted mean concentration of NO_3^--N in tile water from fields in corn production can be greater than 10 mg N L^{-1} (Baker and Johnson, 1981; Randall and Vetsch, 2005) and have been reported as high as 43 mg N L^{-1} (Gast et al, 1978). However, drier conditions that reduce tile flow can result in higher flow-weighted mean concentrations of NO_3^--N in tile water compared to what would commonly be observed (Drury et al., 1993).

Research has shown up to 34% of the annual NO_3^--N loss through tile drainage water occurred during the non-cropping period (Drury et al., 2009). A managed subsurface drainage system (MD) is similar to FD, except for the addition of a water level control structure, which allows for the control of tile drainage flow. Managed drainage has reduced annual water drained 30 to 50% compared to FD (Gilliam et al., 1979; Evans et al., 1995; Drury et al., 2009). Annual reductions in NO_3^--N loss in tile drainage water with MD compared to FD ranged from 32 to 58% (Evans et al., 1990; Fogiel and Belcher, 1991; Drury et al., 2009). The ability to reduce annual NO_3^--N loss through tile drainage water with MD compared to FD was derived from reducing the amount of water drained during the non-cropping period (Evans et al., 1995; Fausey et al., 1995).

Controlled-release, polymer-coated urea fertilizer (PCU) may further reduce NO_3^--N loss in tile drainage water flow. The rate of N release from PCU was a function of moisture and temperature (Fujinuma et al., 2009). In Missouri, PCU applied in April released less than 30% urea-N into the soil by June when broadcast on the soil surface (Nash et al., 2012) and less than 40% when incorporated in the soil at a shallow depth (2-5 cm) (Nelson et al., 2014). The controlled-release of urea-N with this technology could reduce the availability of applied N until later in the growing season when soil conditions are less conducive to environmental N loss and when plant N uptake is greater. Noellsch et al. (2009) reported that PCU increased corn N uptake 24% in a low-lying landscape position compared to non-coated urea (NCU). Nelson and Motavalli (2013) reported PCU increased corn yield 7% compared to NCU with FD.

Combining PCU with MD may greatly reduce early season N loss and increase corn uptake of applied N which could further reduce annual nitrate-N loss through tile drainage water. No research has evaluated the effect of PCU on NO_3^--N loss through tile drainage water flow. With a shift towards continuous corn production in the Midwestern U.S. and increasing environmental concern with water quality regarding N and subsurface tile drainage, research is needed to determine if combining PCU and MD management can reduce annual nitrate-N loss through tile drainage water. The objectives of the study were to 1) quantify the average concentration and annual loss of NO_3^--N in tile drain water from a poorly-drained river bottom soil, and 2) determine whether MD with PCU could reduce NO_3^--N loss in tile water compared to FD with NCU.

MATERIALS AND METHODS

Site Description and Experimental Design

This three-year study (June, 2010 to June 2013) was conducted on a private farm production field in a river bottom soil located in Northeast Missouri (40^{o}3'11.5" N, 92^{o}4' 21.2"W). The investigation was part of a larger project evaluating the effects of subsurface tile drainage and N fertilizer source on continuous corn production (Chapter 5). Subsurface tile drains (10.2 cm diameter, perforated plastic tubing) and water level control structures (AgriDrain Corporation, Adair, IA) were installed in the summer prior to the initiation of the study in April 2010. Tile drains were installed at a depth of 0.9 m with 6.1 m spacings. An additional 6.1 m separated each plot in order to limit movement of water and N into adjacent plots (Fig. 6.1). Plots were 18 by 366 m long. Study years represented the period of time from application of N in the spring until the application of N the following season (Table 6.1).

The study was arranged as a two-way factorial, two-replication, randomized complete-block design. Treatments included drainage (FD and MD) in combination with N fertilizer sources [NCU and PCU (ESN, Agrium Advanced Technology, Denver, CO)]. Nitrogen fertilizer was broadcast applied at 202 kg N ha^{-1} and incorporated into the soil (5-10 cm) directly after application and prior to planting (Sunflower disk harrow, Beloit, KS). Deep tillage (Blu-Jet, SubTiller 4, Thurston Manufacturing Company, Thurston, NE) was used after harvest as a form of residue management. Harvest did not occur in 2010 as a flood in June 2010 resulted in a total crop failure. Field site management including N application rates and dates, plant dates, harvest dates, and water level control with MD can be found in Table 6.1.

The soil type was a Wabash silty clay (fine, smectitic, mesic Cumulic Vertic Endoaquolls) located in a river bottom. Soil samples (composites of three subsamples) were collected from each plot to a depth of 0.0 to 0.3 m, 0.3 to 0.6 m, and 0.6 to 0.9 m in the fall after harvest each year using a Giddings hydraulic probe (Giddings Machine Company, Windsor, CO) fitted with a 4.5 cm diameter steel probe. Soil properties combined over plots are presented by depth over years in Table 6.2 were analyzed using standard soil testing analytical procedures for Missouri (Nathan et al., 2006). Soil NH_4^+-N and NO_3^-N concentrations were converted from mg kg^{-1} to kg ha^{-1} based on soil bulk density measurements taken at the depths of 0-0.3, 0.3-0.6, and 0.6-0.9 m at the field site in 2013. Daily rainfall was measured on-site using a rain gauge and datalogger (Automata, Nevada City, CA) (Fig. 6.2).

Water Sample Collection, Flow, and Nitrate Loss Measurements

Pressure transducers (American Sensor Technologies, Mount Olive, NJ) measured water height year-round in each plot's water-level control structure. Water height was measured every five minutes, and dataloggers stored the data (Automata, Nevada City, CA). During periods of flow in 2012 and 2013, daily water height readings were recorded manually in the water-level control structures using a Little Dipper field instrument (Heron Instruments, Dundas, Ontario), as a means of data quality assurance. Flow rates were obtained by subtracting the height of the slides from the water height readings in the control structures and then using the equation:

$$\text{Flow rate (L m}^{-1}\text{)} = 1.4533 * \text{Flow depth (cm)}^2$$

The equation, obtained through laboratory testing (Chun and Cooke, 2008), was specific to the dimensions of the water-level control structures and angle of the top weir slides used in the study. Flow rates were divided by the area drained (12.2 x 366 m) to obtain measurements of flow over time and area, which estimated total daily flow from each plot.

Portable automated water samplers (Teledyne ISCO, Lincoln, NE) were used in conjunction with liquid level actuators (Teledyne ISCO, Lincoln, NE) to collect water samples every six hours when flow was present. Water samples were combined into daily composite samples. During winter, water samples were manually collected approximately every other day when flow was present. Tile drainage water samples were stored in a refrigerator (5 ^{o}C) and filtered (1.5 µm, 934-AH, Whatman Glass Microfiber, General ElectricBio-Sciences, Pittsburgh, PA) prior to being analyzed for NO_3^--N concentration (10-107-04-1-F Quick Chem) using an automated ion analyzer (Lachat Quik Chem 8000, Loveland, CO).

Statistical Analysis

Soil N concentration, water drained, NO_3^--N loss, and flow-weighted mean concentration of NO_3^- in the tile drainage water by drainage period (FD period, MD period, and cumulative) and study year were statistically analyzed for treatment effects using ANOVA and PROC GLM with SAS v9.3 (SAS Institute, 2013). Soil NH_4^+-N and NO_3^--N concentration after harvest was only affected by depth and year. Water drained, NO_3^- loss, and flow-weighted mean concentration of NO_3^- in the tile drainage water were not affected by N fertilizer source or year, but were affected by subsurface drainage system. Significant differences in treatment means were determined using Fisher's Protected LSD at P = 0.05 or 0.10.

RESULTS AND DISCUSSION

Precipitation

The intensity and distribution of precipitation varied over the three year study (July, 2010 through May, 2013) (Fig. 6.2). High precipitation throughout the 2010 growing season resulted in two flood events (June and September). The first of which resulted in a complete crop failure. Precipitation over the period of July through September, 2010 was 532 mm, which was 280 and 349% greater than in 2012 and 2011, respectively. From October 2010 through March 2011, precipitation totaled 147 mm. Similar to 2010, high intensity precipitation during the spring resulted in a flood event in June; however, crop failure did not occur in 2011. Precipitation over the period of April through June, 2011 was 402 mm, which was 51% greater than in 2012. From July through October 2011, precipitation was low (168 mm) which resulted in drought conditions. Precipitation in November 2011 was high (226 mm), while precipitation from December 2011 through February 2012 was 184 mm which was common for the region and similar to 2010-2011 and 2012-2013. Drought conditions occurred through the spring, summer, and fall in 2012. High intensity precipitation events during the non-cropping period in April and June of 2013 (454 mm) resulted in multiple flooding events.

Soil Nitrogen Concentration

Excessive or lack of precipitation significantly ($P \leq 0.05$) affected soil NH_4^+-N and NO_3^--N after harvest at the depths of 0-0.3, 0.3-0.6 and 0.6-0.9 m over the three-year study (Table 6.3). From 2010 to 2011, soil NH_4^+-N concentration increased from 16.3 to 33.6 kg N ha^{-1} at 0 to 0.3 m depth, 14.6 to 18.4 kg N ha^{-1} at 0.3 to 0.6 m depth, and 12.8 to 16.2 kg N ha^{-1} at 0.6 to 0.9 m depth. Soil NH_4^+ concentration in 2012 compared to

2010 was similar at the 0 to 0.3 m depth, and less at the 0.3 to 0.9 m depth. High soil NH_4^+-N concentration in 2011 was presumably due to low precipitation throughout the summer and fall that limited the conversion of NH_4^+-N to NO_3^--N. Soil NO_3^--N concentration at a 0.3 to 0.9 m depth was similar from 2010 to 2012. However, the soil NO_3^--N at 0 to 0.3 m depth was 14.8 kg N ha^{-1} in 2011 which was lower than 2010 (26.4 kg N ha^{-1}) and 2012 (46.5 kg N ha^{-1}). The relatively high soil NO_3^--N concentration in 2010 was presumably due to high precipitation and limited corn N uptake due to complete crop failure. In 2012, soil NO_3^--N concentration was greater than in 2010 and 2011, which was likely due to drought conditions throughout the spring and summer that limited environmental N loss and corn N uptake which was followed by high precipitation in the fall prior to harvest and soil sampling. Therefore, dry early growing season conditions in combination with wet fall conditions probably increased the potential for NO_3^--N loss during the non-cropping period, and subsequently increased the potential for reducing annual NO_3^--N with MD compared to FD.

Tile Water Drained

Cumulative water drained over each study year ranged from 800 to 1150 mm with FD and 201 to 691 mm with MD (Fig. 6.2). Throughout the three-year study, tile flow was constant with FD and with MD when in FD mode, except for drought periods that began in July and extended into the fall. Persistent tile flow was likely a result of a high water table due to the low landscape position and resulted in high amounts of water drained in relation to the amount of precipitation received. Averaged over the three-year study, MD drained 487 mm which was 52% lower than the 1020 mm drained with FD (Table 6.4). This was similar to greater than the 30 to 50% reductions in annual water flow with MD compared to FD reported in upland soils (Gilliam et al., 1979; Evans et al., 1995; Drury et al., 2009). In two of the three years, tile flow with MD was generally limited to April through June due to mild and extreme drought conditions during the summer and fall. The average reduction in water drained over a study year was due primarily to restricted tile water flow with MD during the summer and non-cropping period. Managed drainage reduced tile flow 86% (84 mm) compared to FD (612 mm) during the summer and non-cropping period. Drury et al. (2009) reported a 44% reduction in water drained with MD compared to FD over the non-cropping period. A greater reduction in water drained over the non-cropping period in this study may be due to greater tile flow over the winter period due to limited freezing of the soil compared to soils in Ontario, Canada.

Nitrate Concentration and Loss in Tile Drainage Water

Cumulative NO_3^--N loss averaged over the three study years ranged from 28.3 (2010-2011) to 90.1 kg N ha^{-1} (2011-2012) with FD (Fig. 6.3), which was likely due to differences in tile flow, soil N concentration, and plant uptake. Previous research studies on continuous corn with FD have reported that annual NO_3^--N loss through tile drainage water increased from 4 to 59 kg N ha^{-1} due to carry-over N (Gast et el., 1978) and 16.5 to 47.8 kg N ha^{-1}due to the application of N in the fall compared to spring (Hernandez-Ramirez et al., 2011). Average NO_3^--N loss through tile drainage water over a study year ranged 12.8 (2012-2013) to 70.2 kg N ha^{-1}(2011-2012) with MD. Similar to Gast et al. (1978), high NO_3^--N loss in the tile drainage water over the 2011-2012 study year was likely due to wet spring conditions and carry-over N, which resulted in approximately 60 kg NO_3^--N ha^{-1} of loss for both FD and MD during the FD period from 9 May through 12

July, 2011. Additionally, a presumably high water table due to the low landscape position of the river bottom soil likely contributed to tile flow and the high annual NO_3^--N loss through the tile drainage water, as compared to the annual 6 to 66 kg NO_3^--N ha^{-1} loss reported in previous research with FD on upland soils in corn production (Jaynes et al., 2001; Randall and Vetsch, 2005; Hernandez-Ramirez et al., 2011; Qi et al., 2011).

Nitrogen fertilizer source did not affect cumulative NO_3^--N loss over the three-year study. Nitrogen presumably was not a limiting factor over the experiment due to dry summer and fall conditions that limited gaseous N loss and corn N uptake in combination with annual applications of 202 kg N ha^{-1}. Averaged over three-years, cumulative NO_3^--N loss though tile drainage water with MD (36.5 kg N ha^{-1}) was significantly ($P \leq 0.10$) reduced 29% compared to FD (51.1 kg N ha^{-1}) (Table 6.4). Previous research studies on upland soils have reported 32 to 58% reduction in annual NO_3^--N loss through tile drainage water with MD compared to FD, which was attributed to reductions in the annual water drained with MD (Evans et al., 1990; Fogiel and Belcher, 1991; Drury et al., 2009). Although water drained over a study year was reduced 52% on average with MD compared to FD, NO_3^--N loss was only reduced by 29%. Higher NO_3^--N concentration in the tile water observed at times with MD compared to FD over the three-year study partially offset the reduction in water drained and subsequent NO_3^--N loss through tile drainage water with MD (Fig. 6.3). Increased NO_3^--N concentration in the tile drainage water with MD compared to FD was likely due the annual reduction in tile flow and limited corn uptake of applied N which may have increase soil N concentration.

Over the FD period, NO_3^--N loss was similar between FD (25.7 kg N ha^{-1}) and MD (28.7 kg N ha^{-1}) on average (Table 6.4). While over the MD period, MD significantly ($P \leq 0.05$)

reduced NO_3^--N loss 69% compared to FD due to an 86% reduction in water drained over that period. In Ontario, Drury et al. (2009) reported a 38% reduction in NO_3^--N loss over the non-cropping period with MD compared to FD, which was due to a 34% reduction in water drained over non-cropping period. Greater reduction in water drained and subsequent NO_3^--N loss over the non-cropping period in this study may have been due to reduced freezing of the soil in Missouri as compared to in Ontario, Canada. These results indicate the potential to reduce the annual NO_3^--N loss from tile drainage with MD may be greater in warmer climates with less potential for freezing of soil during the non-cropping period.

Flow-Weighted Mean Concentration of Nitrate in Tile Drainage Water

Similar to water drained and NO_3^--N loss, flow-weighted mean concentration of NO_3^--N in the tile water was significantly ($P \leq 0.05$) affected by drainage systems during the MD period and the entire study year (Table 6.4). Over the FD period, flow-weighted mean concentration of NO_3^--N in the tile drainage water was similar between MD (6.1 mg N L^{-1}) compared to FD (5.9 mg N L^{-1}). Over the MD period, flow-weighted mean concentration of NO_3^--N in the tile drainage water was 125% greater with MD (10.6 mg N L^{-1}) compared to FD (4.7 mg N L^{-1}). Increased flow-weighted mean concentration of NO_3^--N in the tile water with MD during the MD period as compared to the FD period was likely due to reduced tile flow, which has been reported between growing seasons with FD (Drury et al., 1993)

Average flow-weighted concentrations of NO_3^{-1}-N over a study year were greater with MD (8.1 mg N L^{-1}) compared to FD (5.8 mg L ha^{-1}). Previous tile drainage research in corn production on upland soils have reported annual flow-weighted mean concentration of NO_3^- in tile water in the range of 6 to 43 mg N L^{-1} (Gast et al, 1978;

Baker and Johnson, 1981; Drury et al., 1993; Randall and Vetsch, 2005). Annual flow-weighted mean concentration of NO_3^--N was below what was commonly reported in upland soils in corn production, as well as below the 10 mg N L^{-1} required for drinking water standards (USEPA, 2009). This indicates that subsurface tile draining silty clay river bottom soils may not pose a health concern.

CONCLUSIONS

Similar to previous research on continuous corn in upland soils, cumulative NO_3^--N loss through tile drainage water with FD ranged from 28.3 to 90.1 kg N ha^{-1}. High NO_3^--N loss in the tile drainage water in one of the study years was likely due to carry-over N from the previous season in combination with high tile flow due to wet conditions, as well as a presumably high water table due to the low landscape position that contributed to the tile water flow. Managed drainage was effective in reducing NO_3^--N though the tile drainage water (29%) compared to FD over the three-year study. A reduction in NO_3^--N loss with MD compared to FD was primarily due to reduced tile flow over the non-cropping period. However, reduced tile flow with MD in combination with dry growing season conditions likely limited environmental N loss and corn N uptake during non-flow periods did result in slightly higher NO_3^--N concentration in the tile drainage water with MD compared to FD. However, flow-weighted mean concentration of NO_3^--N was rarely higher than the 10 mg N L^{-1} drinking water standard. Therefore, tile draining river bottom soils for improved continuous corn production may not be a major health risk.

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Table 6.1. Field site management including fertilizer applications, plant and harvest dates, and water level control management with managed drainage during the study.

Field site management	2010	2011	2012
N fertilizer application	28 June 2010	8 May 2011	14 May 2012
Rate (kg N ha^{-1})	202	202	202
Planting date	29 June 2010	9 May 2011	15 May 2012
Rate (seeds ha^{-1})	79,000	79,000	79,000
Harvest date†	--------	7 Nov. 2012	9 Nov. 2012
Water level control – Free drainage mode	28 Jun. 2010	25 Mar. 2011	23 Mar. 2012
Water level control – Managed drainage mode	6 Aug. 2010	13 July 2011	25 May 2012
Water level control – Free drainage mode	--------‡	8 Oct. 2011	--------
Water level control – Managed drainage mode	--------	13 Dec. 2011	--------

† Corn crop was lost in 2010 due to a flood.
‡ Not applicable.

Table 6.2. Selected soil chemical properties from fall soil analysis at depths of 0 to 0.3, 0.3 to 0.6, and 0.6 to 0.9 m in 2010, 2011, and 2012. Data were averaged over tile drainage systems and N fertilized sources.

							Exchangeable (1 M NH_4AOc)				
Year	Depth	pH	Organic matter	Neut. acidity	CEC†	Bray I P	Ca	K	Mg	NH_4^+-N	NO_3^--N
	m	0.01 M $CaCl_2$	g kg^{-1}	--$cmol_c$ kg^{-1} --		mg kg^{-1}	-------------------kg ha^{-1}---------------------				
2010	0-0.3	5.2	26.0	5.1	27.7	46.5	8368	242	992	18.3	24.8
	0.3-0.6	5.3	18.9	4.3	26.4	13.3	8026	191	1071	14.3	11.5
	0.6-0.9	5.6	14.3	2.7	26.1	12.6	8321	208	1243	13.2	9.7
2011	0-0.3	5.4	31.4	4.2	25.5	44.2	7671	395	1003	32.9	14.1
	0.3-0.6	5.9	24.6	2.4	26.3	11.6	8422	371	1252	18.2	11.5
	0.6-0.9	6.3	18.5	0.9	24.2	6.3	8117	387	1284	15.6	8.8
2012	0-0.3	5.1	26.8	5.8	25.8	58.4	7255	256	928	16.1	47.7
	0.3-0.6	5.5	20.3	3.7	25.5	9.5	7745	220	1155	5.5	14.1
	0.6-0.9	5.9	14.9	2.0	23.7	4.2	7575	219	1208	5.3	6.7

† Abbreviations: CEC = cation exchange capacity; Neut. = neutralizable.

Table 6.3. Effect of year and depth on soil NH_4^+-N and NO_3^--N concentrations after harvest. Data were averaged over N fertilizer source and drainage treatments.

	Soil NH_4-N			Soil NO_3^--N		
Depth (m)	2010	2011	2012	2010	2011	2012
	------- kg N ha^{-1} -------			------ kg N ha^{-1} ------		
0-0.3	16.3	33.6	16.4	26.4	14.8	46.5
0.3-0.6	14.6	18.4	5.6	11.2	11.3	13.2
0.6-0.9	12.8	16.2	5.1	9.8	8.5	6.1
LSD (*P*= 0.05)	----------- 3.7 -----------			----------- 9.1 ----------		

Table 6.4. Effect of drainage water management system on tile water drained, NO_3^--N loss through tile water flow, and flow-weighted mean concentration of NO_3^--N averaged over three years.

	Tile water drained†			NO_3^--N loss through tile water			Flow-weighted mean		
Drainage	FD period‡	MD period	Cumulative§	FD period	MD period	Cumulative	FD period	MD period	Annual
	------------------- mm -------------------			-------------- kg NO_3^--N ha^{-1} --------------			----------- mg NO_3^--N L^{-1} -----------		
FD	407	612	1020	25.7	25.4	51.1	5.9	4.7	5.8
MD	404	84	487	28.7	7.8	36.5	6.1	10.6	8.1
LSD¶	NS	112*	85*	NS	8.6*	12.2	NS	3.0*	1.8*

† Abbreviations: FD = free drainage; LSD = least significant difference; MD = managed drainage; NS = not significant.

‡ FD period represents the period of time that tile flow was not restricted with MD, while MD period represents the period of time when tile flow was restricted with MD.

§ Cumulative or annual represents the period of time from application of N at planting until the application of N in the following year.

¶ A single asterisk following an LSD value represents a P-level of 0.05 and no asterisk represents a P-level of 0.10.

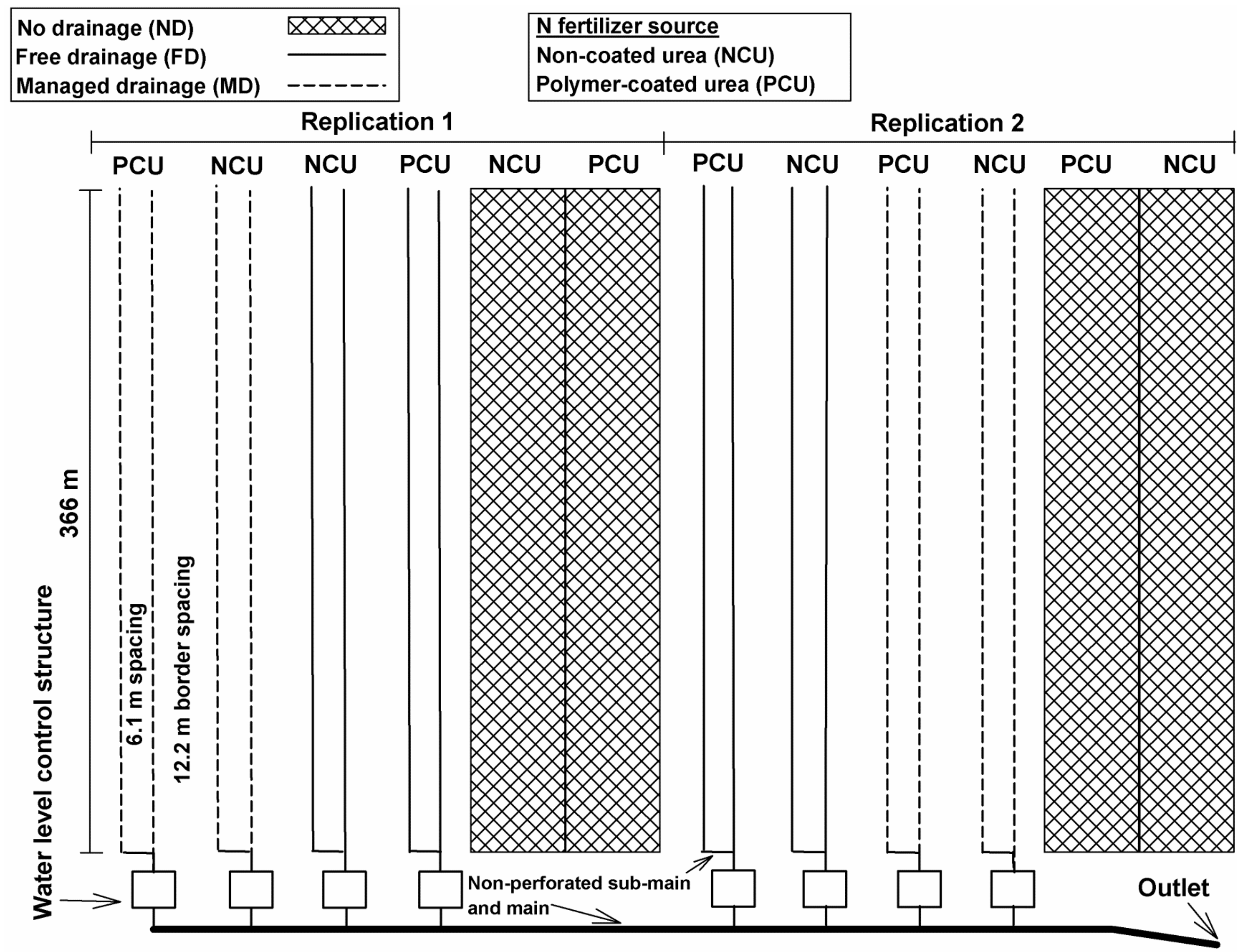

Figure 6.1. Field layout and plot treatments, including the subsurface tile drainage design.

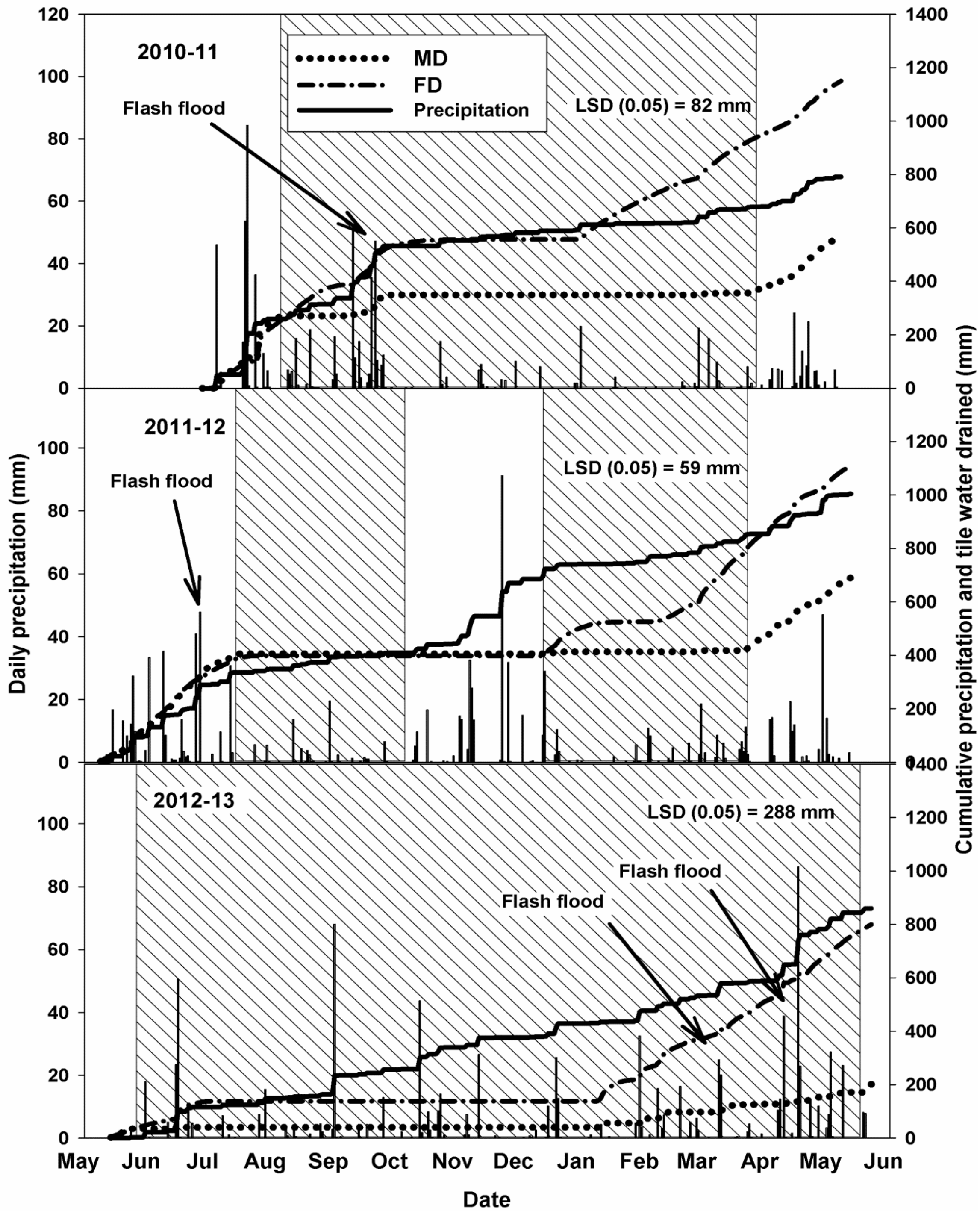

Figure 6.2. Daily precipitation (bars), cumulative precipitation (solid lines), and tile water drained (dashed/dotted lines) by tile drainage system (FD = free drainage system and MD = managed drainage system) and years. The start of each study year corresponds to the spring N application. Shaded areas represent the period of time that MD treatments were in managed drainage mode.

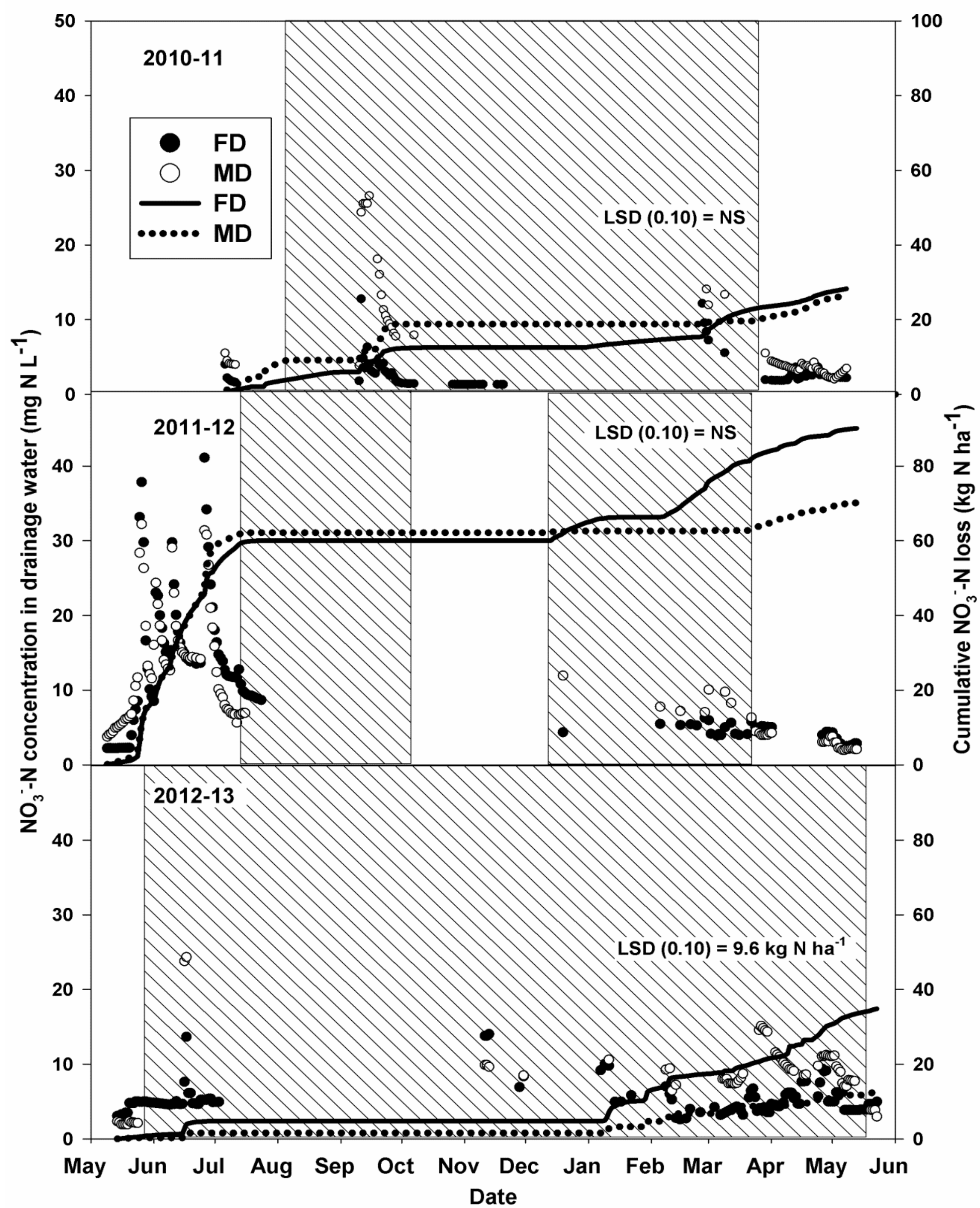

Figure 6.3. Daily concentration of NO_3^--N in tile drainage water (circles) and cumulative NO_3^--N loss (lines) by tile drainage treatment (FD = free drainage system and MD = managed drainage system) and years. The start of each study year corresponds to the spring N application. Shaded areas represent the period of time that MD treatments were in managed drainage mode. NS = not significant.

CHAPTER 7

SUBSURFACE DRAINAGE SYSTEMS FOR INCREASED WINTER RYE AND SORGHUM FORAGE YIELDS

ABSTRACT

As livestock demand and production continue to rise in the United States, there is a greater need for increased forage production and improved forage quality. Forage production on soils with production restrictions, such as poorly-drained, floodplain soils may have the greatest potential to increase to meet future demands. The objectives of the study were to evaluate the impact of free (FD) and managed drainage systems (MD) on yields and nitrogen (N) uptake of winter rye (*Secale cereale* L.) and forage sorghum [*Sorghum bicolor* (L.) Moench], and to determine the effects of these drainage systems on nitrate concentration in the forage. Managed subsurface drainage did not increase forage biomass production compared to FD. The presence of subsurface drainage (both FD and MD) increased total forage biomass production 27 to 32% compared to ND. Annual plant N uptake was increased 30% with MD and 41% with FD compared to ND, when averaged over the four-year study. Nitrate concentrations in winter rye biomass were at safe levels over the four-year study. However, regardless of the presence or absence of drainage, nitrate concentrations in sorghum in two study years ranged from 1310 to 4520 mg kg^{-1} which corresponded to toxic to extremely toxic levels. Dry summer months may have contributed to the high nitrate concentrations observed in the forage sorghum biomass. Subsurface drainage may provide farmers with an opportunity to increase annual forage production that may be important in typical cool-season, tall fescue production areas.

INTRODUCTION

The United States beef cattle industry has increased in value by 32% from 2002 to 2011 and is presently estimated to be worth $79 billion dollars (USDA, 2013). As livestock demand and production continue to rise, there is a greater need for increased forage production and improved forage quality. Missouri ranks second in the number of cows in the United States (USDA, 2014). Forage production on soils with production restrictions, such as poorly-drained, floodplain soils, may have the greatest potential to increase to meet future demands.

Annual forage crop rotations, such as winter rye and forage sorghum, are viable pasture systems in Missouri. Winter rye usually needs to be planted in September and under normal weather conditions in order to produce enough forage to be grazed in November (University of Missouri, 2012) and can remain in a vegetative growth stage through April. Sorghum is typically planted in June or July (University of Missouri Extension, 2001). The greatest production concern with winter rye in poorly-drained soils is growth and survival under saturated soil conditions. Extended periods of saturated soil conditions during a growing season may severely lower forage production by inhibiting seed germination (University of Missouri Extension, 2013), plant growth (Licht and Al-Kaisi, 2005), and increase the incidence of disease, and nutrient loss (Drury et al., 1999; Drury et al., 2006). The potential for soil compaction increases with water content (Unger and Kaspar, 1994) and can be a major concern in forage grazing systems due to the traffic of livestock and farm equipment. Soil compaction has been found to reduce root growth and crop yield (Sweeney et al., 2006).

A high concentration of nitrate in forage biomass can pose serious health risks to livestock if consumed including suppressed appetite, lower rate of weight gain, lower milk production (Hibbs et al., 1978; Osweiler et al., 1985; Undersander et al., 1999), and death in severe instances (MacKown and Weik, 2004). Forage biomass with nitrate-N concentration below 1000 mg kg^{-1} is generally considered safe for livestock consumption (Undersander et al., 1999). Sorghum that is bred with a trait for reduced lignin content for animal feed, termed “forage sorghum” is thought to have a higher potential for nitrate accumulation in the plant biomass compared to most other forage crops grown in Missouri (University of Missouri Extension, 2012). Drought conditions are common during the summer months in Northeast Missouri and may increase the potential for nitrate accumulation in forage sorghum biomass (Larson, 2006).

Free subsurface drainage (FD) has been found to increase row crop production in many poorly-drained soil environments (Fausey et al., 1983; Kladivko et al. 2005; Nelson et al., 2009; Nelson and Smoot, 2012; Nelson and Motavalli, 2013). Installation of subsurface tile drains can reduce saturated soil conditions near the soil surface and plant root zone (Kalita and Kanwar, 1993). Additionally, FD can mitigate issues of trafficability that can delay farming activities, such as fertilizer, herbicide, and pesticide applications, as well as planting, and harvesting (Fisher et al., 1999). Due to these benefits, FD on average has been reported to increase corn grain yield by 18% (Nelson and Motavalli, 2013) and soybean grain yield by 10% (Nelson et al., 2011) compared to the absence of drainage (ND) in poorly-drained soils.

Recent advances in subsurface drainage technology now allow for the management of the tile outlet height with the addition of a water level control structure, thereby effectively allowing for the regulation of the water table height and drainage outflow (Fouss et al., 1999). During dry periods of a cropping season, managed subsurface drainage (MD) has been reported to increase the retention of crop-available water and crop nutrients in the root zone (Wesström and Messing, 2007). A two year study conducted in Canada reported increased corn grain yield (1-5%) and soybean grain yield (3-10%) with MD compared to FD (Drury et al., 2009).

Research evaluating FD and MD has been limited to field crops, such as corn and soybeans. No research has evaluated the impact of subsurface drainage systems on forage production. We hypothesize that improving soil drainage in poorly-drained soils with tile drainage should improve plant growth conditions and subsequent forage yields as commonly reported with field crop systems. As forage prices continue to increase, the potential to improve forage quality and production in poorly-drained soils with the addition of subsurface drainage could become an economically viable management option. The objective of this study was to evaluate the impact of FD and MD on N uptake and yield of winter rye and forage sorghum compared to ND in a poorly-drained soil. Additionally, due to the severe drought in 2012 and the continued concern over nitrate concentration in forage crops, forage samples were analyzed for nitrate concentration to determine whether and when toxic nitrate levels were present in winter rye and sorghum biomass, as well as the impact subsurface drainage may have had on the issue of nitrate toxicity in forage crops.

MATERIALS AND METHODS

Site Description and Experimental Design

The four-year study was initiated in September 2009 at the University of Missouri's Greenley Memorial Research Center (40° 1' 17" N, 92° 11' 24.9" W) in Northeastern Missouri. The soil series was a Blackoar silt loam (fine-silty, mixed, superactive, mesic Fluvaquentic Endoaquolls). Soil samples (composite of three samples) were taken from each plot at depths of 0 to 0.3, 0.3 to 0.6, and 0.6 to 0.9 m in the fall of 2011, 2012, and 2013 with a Giddings Probe (Giddings Machine Company, Windsor, CO). Soil properties were analyzed using standard soil test procedures for Missouri (Nathan et al., 2006) (Table 7.1). Soil NH_4^+-N and NO_3^-N concentrations were converted from mg kg^{-1} to kg ha^{-1} based on soil bulk density measurements taken at the depths of 0-0.3, 0.3-0.6, and 0.6-0.9 m at the field site in 2013. There were two replications and plot sizes were 37 by 91 m and 37 by 305 m in replications one and two, respectively. Subsurface tile drainage systems, including the water level control structures were installed in Aug., 2009. The subsurface tile drains were installed at a 0.91 m depth with 18.3 m spacing, and ran the length of the plots. In each replication, there was a FD, MD, and ND treatment.

The experimental field site was in a winter rye and brown mid-rib forage sorghum rotation and was grazed under a rotational beef cattle (*Bos tauurus* Aberdeen angus) grazing program. The field site was divided into sections perpendicular to the plots in order to maintain a uniform cattle stocking rate (19 head ha^{-1}) across the entire field site. Vertical tillage was done directly before winter rye cultivar 'VNS' was broadcast at 111 kg seed ha^{-1} with a fertilizer cart. Brown midrib forage sorghum cultivars (NUTRI+PLUS in 2011, TD7000 in 2012, and Trophy II in 2013) were NT seeded in the summer at 18 to 23 kg ha^{-1} with 76 cm spacing in 2011and 2012, and 38 cm spacing in 2013. Sorghum was not planted in the summer of 2010 due to wet soil conditions. Prior to cattle grazing events, aboveground biomass was randomly collected throughout each plot representing a total area of 2.3 m^2. Biomass samples were dried and weighed to determine biomass yields. Biomass samples were ground using a Wiley-Mill to pass a 1-mm sieve (Isaac and Jones, 1972) and analyzed for total N concentration by combustion using a total C:N analyzer (LECO, TruSPEC CN Analyzer, St. Joseph, MI) and additionally analyzed for nitrate-N concentration (Quik Chem, 13-107-04-1-A) in 2011-2013. Management information including planting and herbicide, fertilizer applications, and harvest dates are reported in Table 7.2. Daily precipitation values were obtained from the nearby Greenley Memorial Research Center weather station (Campbell Scientific, Logan, UT).

Statistical Analysis

A two-way ANOVA was used to assess the impact of subsurface drainage systems on biomass yields, plant N uptake, and nitrate concentration in the biomass. For the purpose of this study, a year encompassed a single rotation of winter rye and forage sorghum which spanned the period of October through September. For each year the harvest yields and the amount N taken up by the crops were summed, while nitrate-N concentration in the biomass was averaged over individual harvests within each year. Biomass yields, plant N uptake, and nitrate concentration in the biomass were pooled over years due to absence of a significant ($P \leq 0.10$) interaction with subsurface drainage treatments. Within each year, one-way ANOVA was performed on the repeated measurements of biomass yields, plant N uptake, and nitrate concentration. All statistical analyses were conducted using the SAS v9.3 statistical program (SAS Institute, 2013) and PROC GLM to determine if there were significant treatment effects. Fischer's Protected LSD at P = 0.10 (individual harvests) or 0.05 (annual harvest) was used to separate means and determine significant treatment effects.

RESULTS AND DISCUSSION

Precipitation

From 2000 to 2009, annual precipitation at the study site over the period of October through September averaged 984 mm (Fig. 7.1) (University of Missouri Extension, 2013). Total precipitation (October through September) exceeded the prior nine-year average by 56% in 2009-2010, while total precipitation was below average by 28, 19, and 6% in 2010-2011, 2011-2012, and 2012-2013, respectively. In Northeastern Missouri, precipitation usually exceeds the rate of evapotranspiration in the spring months, while mild drought conditions typically occur over the summer months. Excessive precipitation occurred throughout the entire 2009-2010 study year and in the spring of 2013. Drought conditions were experienced in the fall/winter of 2010-2011 and over the summer in every study year except 2009-2010. Flooding of the field site occurred in the summer of 2010 and early in the spring of 2013.

Forage Biomass Yields

The combined, annual biomass production of winter rye and sorghum was significantly ($P \leq 0.05$) affected by the presence and absence of subsurface drainage when averaged over the four-year study (Fig. 7.2). Managed subsurface drainage and FD yielded 5.6 and 5.8 tons ha^{-1} of total annual biomass on average, respectively. The ND treatment averaged 4.4 tons ha^{-1} of total annual biomass, which was significantly less with the presence of drainage (FD or MD). Increased biomass production with the addition of a subsurface drainage represented a 27 and 32% increase compared to ND with MD and FD, respectively.

Winter rye and sorghum biomass production varied among individual biomass harvests taken prior to cattle grazing events due to differences in climatic conditions over the four-year study (Fig. 7.3). Although not always significant, the presence of subsurface drainage appeared to increase biomass production of winter rye and sorghum throughout the four-year study. In 2010, due to a series of intense rainfall events in the spring and summer, wet field conditions led to only a single winter rye harvest/grazing event and made the planting of sorghum in the summer not possible. Although not significant ($P \leq 0.10$), winter rye biomass harvested directly prior to the April grazing event increased upon the 2.1 tons ha^{-1} produced with ND by 71 and 132% with MD and FD, respectively.

In 2010-11, there were three winter rye harvests (Nov., Apr., and July) and two sorghum harvests (Aug. and Sept.). Fall harvest of winter rye prior to the winter period is common in Missouri under normal weather conditions (University of Missouri, 2012). There was no significant difference in biomass production among drainage treatments at any individual harvest date. However, although not significant, the first winter rye harvest that occurred in the fall did increase from 0.1 to at least 0.5 metric tons ha^{-1} with the presence of subsurface drainage. Sorghum biomass production was not affected by the presence or absence of subsurface drainage in 2011. This result was likely due to dry conditions in the summer months that resulted in minimal drainage events (Chapter 8) and the subsequent increase in sorghum biomass production with the addition of subsurface drainage.

In 2011-12, there were three winter rye harvests (Mar., April, and June) and only a single sorghum harvest that occurred in September due to abnormally dry conditions in the summer. The first winter rye harvest was the only harvest to have a significant difference in biomass production among the drainage treatments. At the March harvest of winter rye, biomass was found to be significantly increased from 0.7 to 1.6 tons ha^{-1} with FD compared to ND. Although not significant, the presence of a subsurface drainage system (FD or MD) produced 79% greater sorghum biomass than ND. Increased sorghum production with subsurface drainage in a generally dry year was likely due to wet field conditions early in the growing period. The ability to lower the water table with subsurface drainage has been shown to improve early root development with soybean (Stanley et al., 1980) which presumably would improve the plant-water use efficiency over the dry summer growth period (Lorens et al., 1987; Skinner, 2008).

There were two winter rye harvests (Nov. and May) and three sorghum harvests (July, Aug., and Sept.) in 2012-13. Similar to 2011-12, the first winter rye harvest was the only harvest in which a significant difference in biomass production was observed among drainage treatments. At the November harvest, forage biomass increased from 1.3 to 1.7 tons ha^{-1} with FD compared to ND. Severe drought conditions in the summer, similar to that in 2012, likely resulted in no differences in sorghum biomass production among drainage treatments.

Plant Nitrogen Uptake

The annual amount of N taken up by winter rye and sorghum was significantly ($P \leq 0.05$) affected by the presence and absence of subsurface drainage when averaged over the four years (Fig. 7.4). Total annual plant N uptake increased 44 (30%) and 62 (41%)

kg N ha^{-1} with MD and FD compared to ND, respectively. However, total N concentration in winter rye and sorghum biomass was not significantly affected by the presence or absence of subsurface drainage when averaged over the four-year study (data not presented). Therefore, increased annual N taken up in the forage biomass with subsurface drainage (FD or MD) was presumably due to improved crop establishment, early growth, and subsequent biomass production compared to ND. These results are consistent with a ten-year study evaluating corn response to drainage spacing which found that plant population and early plant growth rate increased with proximity to the tile drains in multiple years (Kladivko et al., 2005).

Similar to the biomass yield, the amount of N taken up by winter rye and sorghum only significantly ($P \leq 0.10$) differed among drainage treatments prior to selected cattle grazing events throughout this study (Fig. 7.5). In 2010-11, plant N uptake did not significantly differ among treatments at any individual harvest dates. Plant N uptake in 2010-11, ranged from 25 to 53 kg N ha^{-1} and 24 to 55 kg N ha^{-1} from individual winter rye and sorghum harvests, respectively.

In 2011-12, the first winter rye harvest (March) was the only harvest date within this study year to have differences in plant N uptake among treatments, which paralleled the biomass yield analysis. At the March harvest, the average amount of plant N uptake with FD was 70 kg N ha^{-1} which was significantly greater than the 28 kg N ha^{-1} taken up with ND. Subsequent winter rye harvests in this study year ranged from 17 to 35 kg N ha^{-1}. Sorghum plant uptake of N at the September harvest ranged from 67 to 138 kg N ha^{-1} which corresponded to the ND and FD treatment, respectively. Although not significantly different, sorghum N uptake increased by 79 and 104% with MD and FD compared to ND, respectively.

In 2012-13, the first winter rye harvest of the study year was the only time in which there were significant differences in plant N uptake among drainage treatments. At this harvest, plant N uptake with FD averaged 83 kg N ha^{-1} which was significantly greater than the 55 and 63 kg N ha^{-1} taken up by MD and ND, respectively. Plant N uptake with sorghum in this study year ranged from 22 to 31 kg N ha^{-1} for the first two harvest dates and 9 to 14 kg N ha^{-1} for the final harvest.

Whole Plant Nitrate-N Concentration

Unlike biomass yield and plant N uptake analysis, the whole plant nitrate concentration averaged over a study year was not significantly ($P \leq 0.10$) increased by the presence of subsurface drainage. However, whole plant nitrate concentration response did vary over the three years due to the type of forage crop and weather (Fig. 7.6). Whole plant nitrate concentration in winter rye never exceeded 1040 mg kg^{-1} at any time over the study and there were no significant differences in nitrate concentration in winter rye biomass among treatments at any harvest date. Therefore, nitrate toxicity does not appear to be a concern with winter rye under the conditions observed during this study. However, nitrate concentration in forage sorghum over two of the three years, regardless of the drainage treatment, ranged from 1310 to 4520 mg NO_3^--N kg^{-1} which corresponded to toxic to extremely toxic levels (Evans et al., 2012). High nitrate accumulation in forage sorghum biomass may have been due to the extreme drought conditions experienced during the summer months in 2012 and 2013. However, the lack of plant available water may not be the only factor in whether or not nitrate toxicity is a concern in sorghum. In

2011, there were mild drought conditions present over the growing period, but nitrate levels were still found to be above a toxic level at both harvests for all treatments. In 2012 and 2013, there was a significant lack of precipitation over the summer months leading to serious concern in the region over nitrate toxicity in forage crops. However, 2013 had the only instances were nitrate concentration in sorghum was below toxic levels. Non-toxic nitrate concentration in forage sorghum biomass in 2013 over three harvests may have been due to cooler temperatures compared to 2012 which presumably mitigated the lack of precipitation.

CONCLUSIONS

The presence of subsurface drainage (FD or MD) increased overall biomass production in the annual pasture system including winter rye and sorghum. However, MD did not increase biomass production compared to FD and factoring in the extra cost with installation of MD compared to FD, and the limited potential environmental concerns with nitrate loss with this type of forage production system, FD is the more practical and economical management option to increase forage production. Increased biomass production with subsurface drainage corresponded with increased plant N uptake compared to ND. Nitrate toxicity in whole plant samples of winter rye was not observed under the conditions of this study, but was a concern with forage sorghum. This result was likely due to the climate in Northeast Missouri, which typically experiences excessive precipitation over the winter rye growth period and a lack of precipitation in combination with high air temperatures over the sorghum growth period. However, whole plant nitrate content in sorghum varied over three years with similar weather conditions which indicated that determining whether to test biomass material for nitrate toxicity should not be based solely on weather conditions. Subsurface tile drainage provides farmers with an opportunity to increase annual forage production that may be important for typical cool-season, tall fescue production areas.

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Table 7.1. Select soil chemical properties from fall soil samplings from depths of 0 to 0.3, 0.3 to 0.6, and 0.6 to 0.9 m in 2011, 2012, and 2013. Data were averaged over drainage treatments in the fall of 2011, 2012, and 2013.

							Exchangeable (1 M NH_4AOc)				
Year	Depth	pH	Organic matter	Neut. acidity	CEC†	Bray I P	Ca	K	Mg	NH_4^+-N	NO_3^--N
	m	0.01 M $CaCl_2$	g kg^{-1}	--cmol$_c$ kg^{-1} --		mg kg^{-1}	------------------kg ha^{-1}---------------------				
2011	0-0.3	5.2	22	4.4	14.9	35.6	3749	211	497	44.6	87.8
	0.3-0.6	4.8	16	4.9	14.4	42.1	3268	184	550	62.8	36.8
	0.6-0.9	4.9	23	5.4	16.9	45.0	4029	286	576	36.4	72.2
2012	0-0.3	5.6	28	3.5	15.0	40.9	4244	230	465	18.6	98.6
	0.3-0.6	4.9	16	5.8	13.5	29.3	2709	160	417	16.2	26.1
	0.6-0.9	4.4	12	9.3	20.9	19.0	3698	216	851	15.1	8.7
2013	0-0.3	5.5	28	4.2	15.9	51.1	4338	250	477	16.7	21.0
	0.3-0.6	4.7	12	6.8	15.2	36.0	2920	164	475	16.4	7.5
	0.6-0.9	4.6	13	6.7	16.1	23.3	3153	189	591	20.8	8.5

† Abbreviations: CEC = cation exchange capacity; Neut.= neutralizable.

Table 7.2. Maintenance fertilizer, crop protection products, and winter rye and sorghum planting and harvest dates from 2009-2013.

Field management and harvest information	2009-2010	2010-2011	2011-2012	2012-13
Winter Rye				
Seeding date	15 Sept. 2009	2 Sept. 2010	4 Sept. 2011	14 Sept. 2012
Application rate	111 kg ha^{-1}	111 kg ha^{-1}	111 kg ha^{-1}	111 kg ha^{-1}
Fall fertilizer application - N–P_2O_5 –K_2O (kg ha^{-1})	45-0-0	56-0-0	--------------	--------------
Application date	14 Sept. 2009	2 Sept. 2010	--------------	--------------
Pesticide application date[†]	11 Sept. 2009	--------------	--------------	19 Sept. 2012
Glyphosate (N-(phosphonomethyl)glycine)	--------------[§]	--------------	--------------	1.53 kg a.e. ha^{-1}
2,4-D (2,4-Dichlorophenoxyacetic acid)	--------------	--------------	--------------	0.52 kg a.e. ha^{-1}
Paraquat dichloride[‡]	0.77 kg a.e. ha^{-1}	--------------	--------------	
Spring fertilizer application - N–P_2O_5 –K_2O (kg ha^{-1})	--------------	45-0-0	--------------	56-0-0
Application date	--------------	30 Mar. 2011	--------------	21 Mar. 2013
Biomass harvest				
Fall/Winter harvest date	--------------	11 Nov. 2010	26 Mar. 2012	16 Nov. 2012
Early Spring harvest	23 April 2010	13 April 2011	22 April 2012	24 April 2013
Spring harvest date	--------------	5 July 2011	4 June 2012	--------------
Sorghum				
Seeding date	--------------	7 July 2011	19 June 2012	14 June 2013
Application rate	--------------	23 kg ha^{-1}	20 kg ha^{-1}	18 kg ha^{-1}
Summer fertilizer application - N–P_2O_5 –K_2O (kg ha^{-1})	--------------	67-44-89	56-0-0	56-0-0
Application date	--------------	8 July 2011	19 June 2012	14 June 2013
Pesticide application date[†]	--------------	6 July 2011	19 June 2012	14 June 2013
Glyphosate (*N*-(phosphonomethyl)glycine)	--------------	1.53 kg a.e. ha^{-1}	1.53 kg a.e. ha^{-1}	1.53 kg a.e. ha^{-1}
2,4-D (2,4-Dichlorophenoxyacetic acid)	--------------	0.52 kg a.e. ha^{-1}	0.52 kg a.e. ha^{-1}	0.52 kg a.e. ha^{-1}
Biomass harvest				
harvest date (#1)	--------------	--------------	--------------	12 July 2013
harvest date (#2)	--------------	8 Aug. 2011	--------------	6 Aug. 2013
harvest date (#3)	--------------	28 Aug. 2011	13 Sept. 2012	26 Aug. 2013

† Application included 0.25% vol./vol. nonionic surfactant.

‡ Paraquat dichloride (1,1'-dimethyl-4,4'-bipyridinium dichloride) 3.

§ None-applied

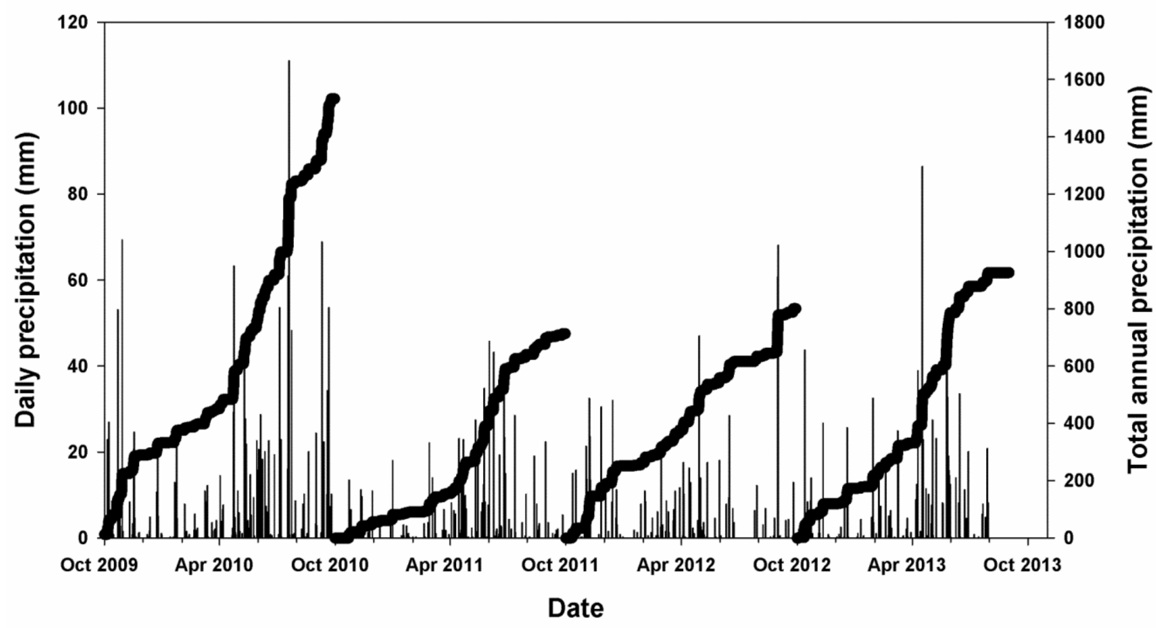

Figure 7.1. Daily (bars) and cumulative (lines) rainfall over the period of October through September at the University of Missouri, Greenley Memorial Research Center from 2009-2013.

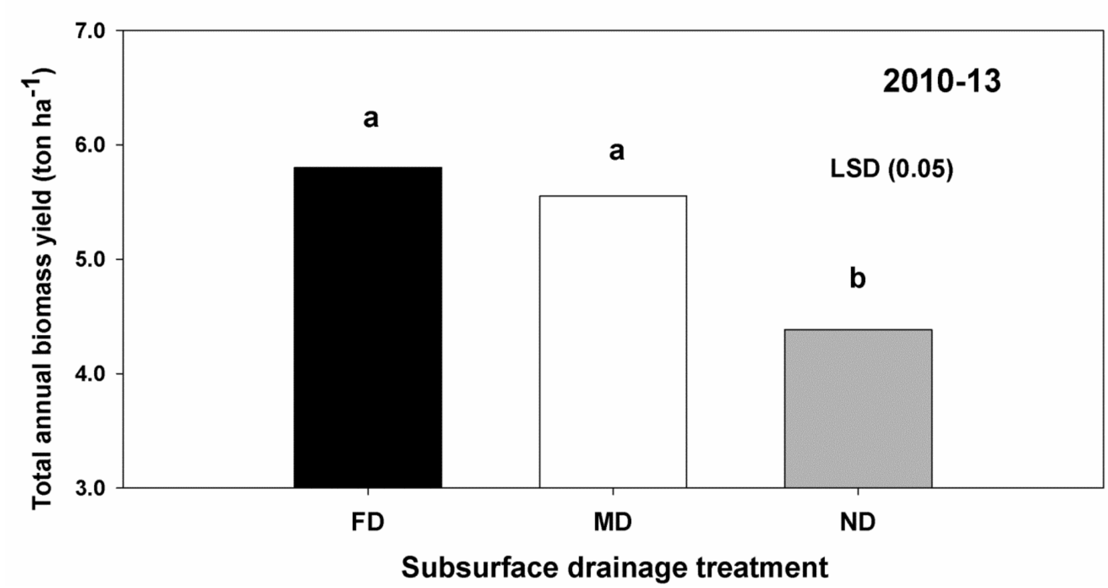

Figure 7.2. Total annual forage yield (winter rye and sorghum) over the period of October through September, averaged over 2009-10, 2010-11, 2011-12, and 2012-13. Letters over drainage treatments (FD, free subsurface drainage; MD, managed subsurface drainage; ND, no subsurface drainage) represent differences in yield using Fisher's Protected LSD ($P \leq 0.05$).

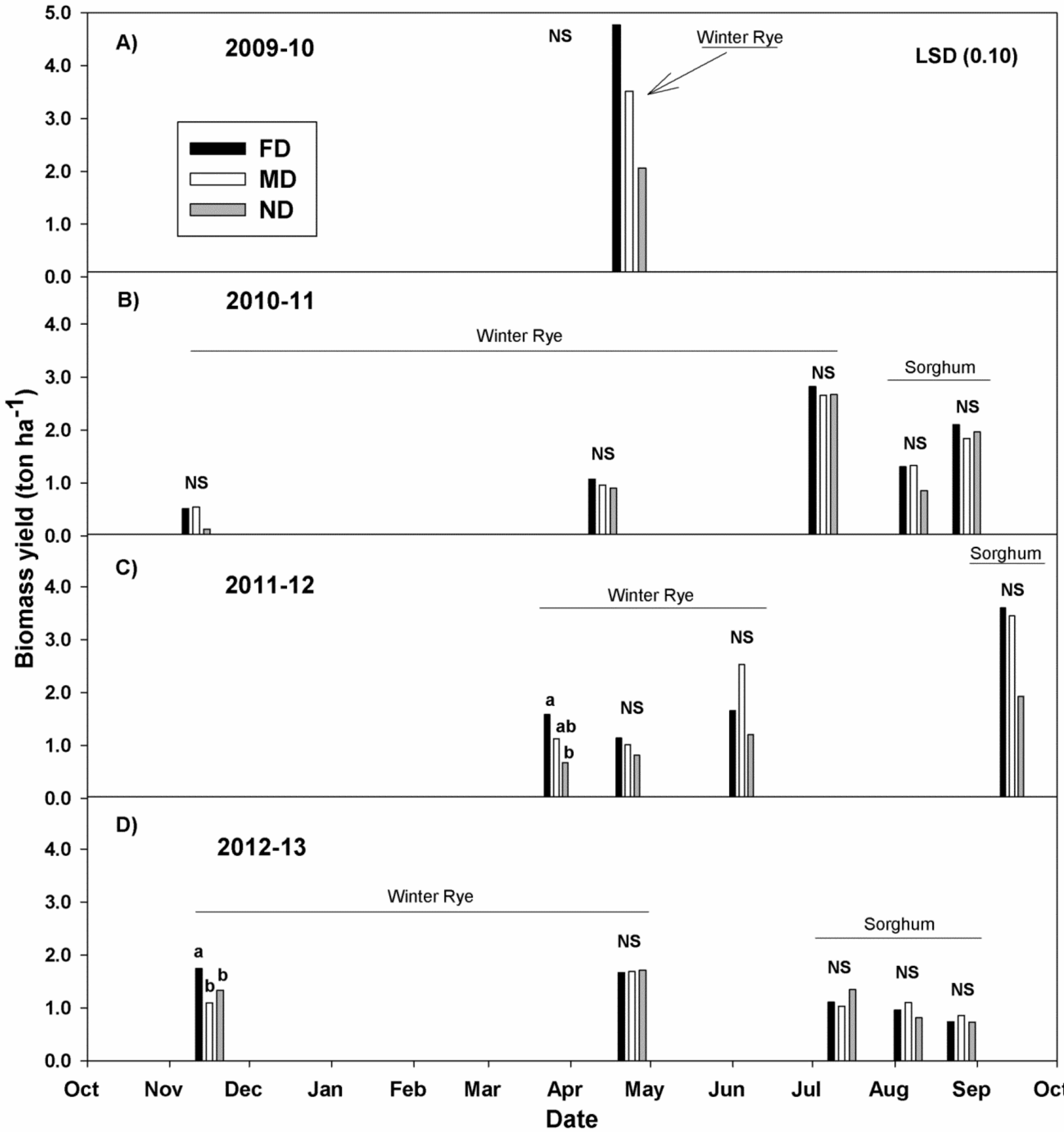

Figure 7.3. Individual annual forage winter rye and sorghum biomass yields harvested prior to cattle grazing events from October, 2009 through September, 2013. Letters over drainage treatments (FD, free subsurface drainage; MD, managed subsurface drainage; ND, no subsurface drainage) represent differences in biomass yields within individual forage harvests using Fisher's Protected LSD ($P \leq 0.10$).

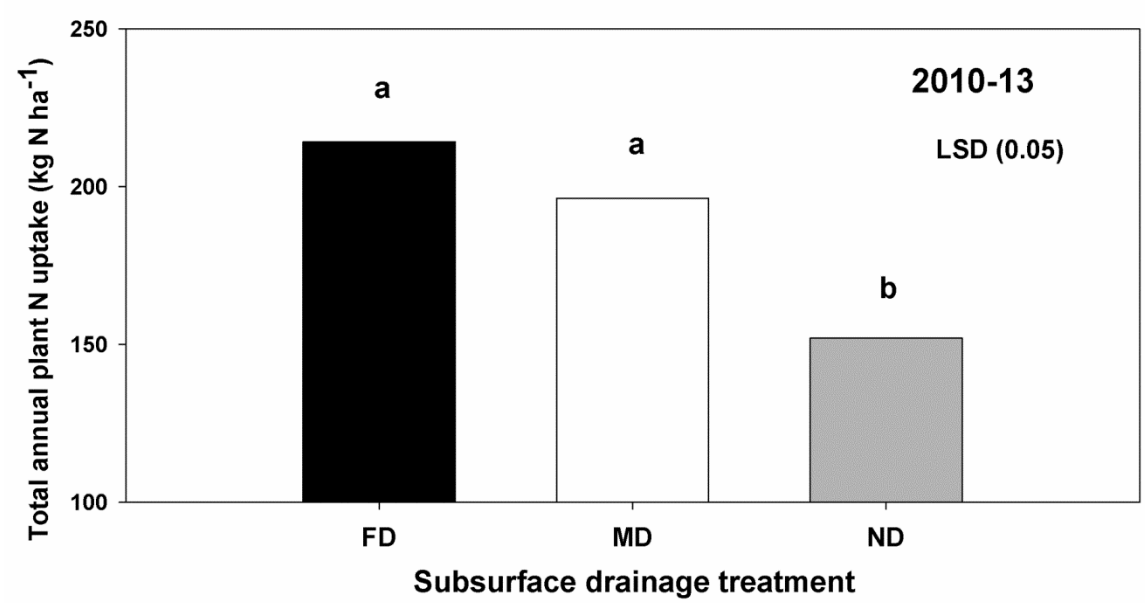

Figure 7.4. Total annual forage (winter rye and sorghum) N uptake over the period of October through September, averaged over 2009-10, 2010-11, 2011-12, and 2012-13. Letters over subsurface drainage treatments (FD, free subsurface drainage; MD, managed subsurface drainage; ND, no subsurface drainage) represent differences in plant N uptake using Fisher's Protected LSD ($P \leq 0.05$).

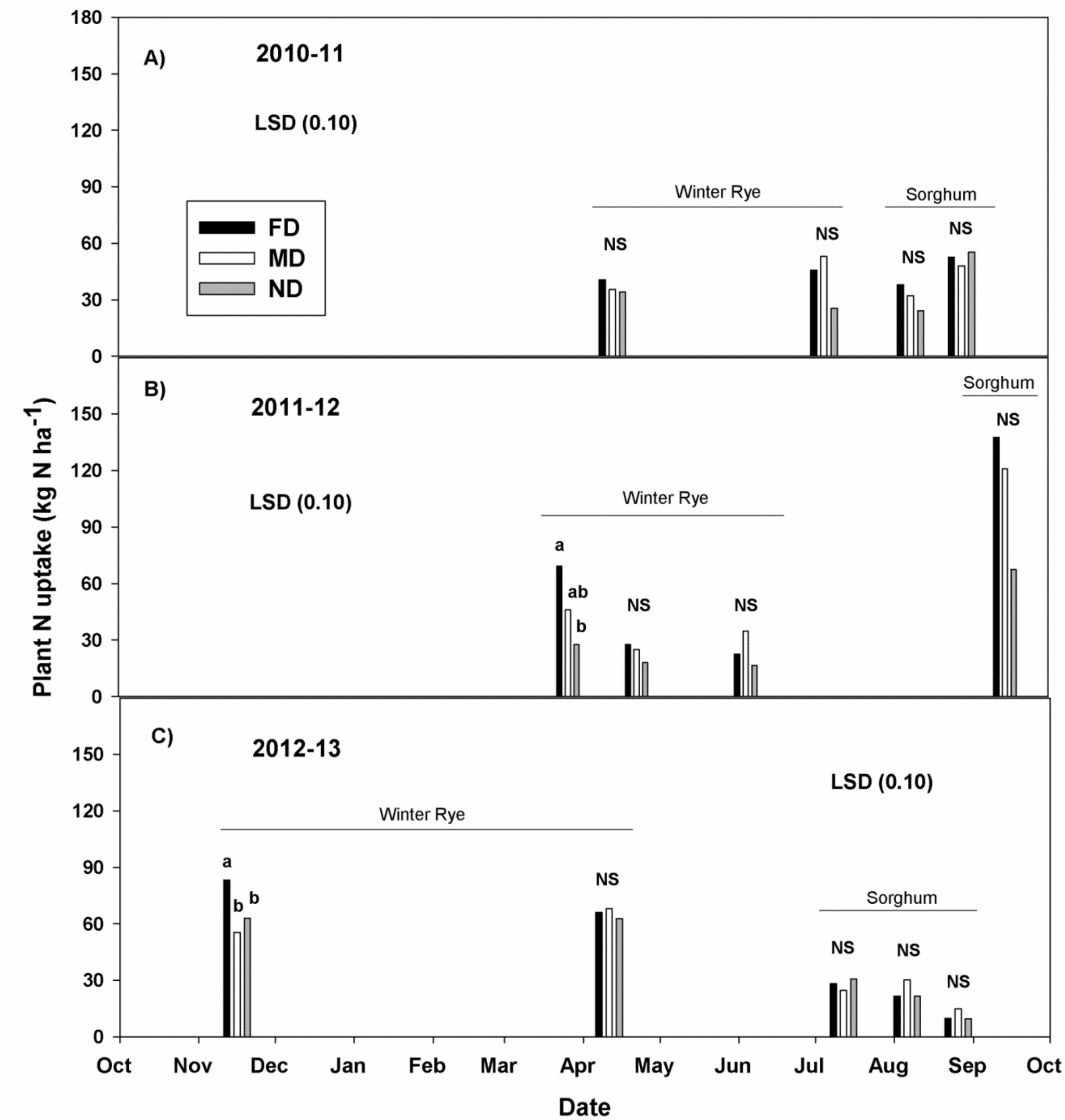

Figure 7.5. Individual annual forage (winter rye and sorghum) N uptake measured from harvests taken directly prior to cattle grazing events from October, 2009 through September, 2013. Letters over drainage treatments (FD, free subsurface drainage; MD, managed subsurface drainage; ND, no subsurface drainage) represent differences in biomass yields within individual forage harvests using Fisher's Protected LSD ($P \leq 0.10$).

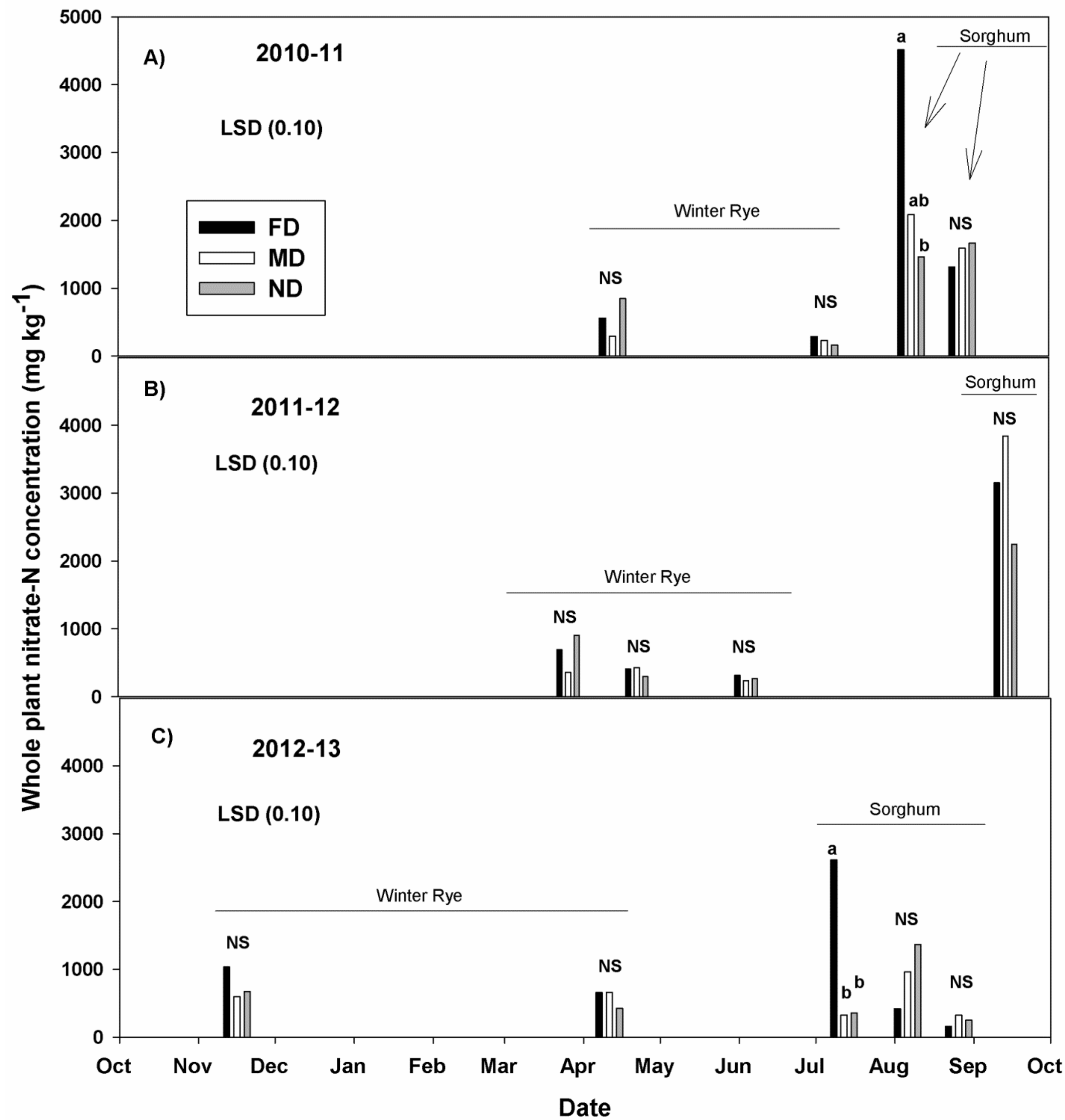

Figure 7.6. Nitrate-N concentration in whole plant samples of winter rye and sorghum collected prior to cattle grazing events over the period of October, 2009 through September, 2013. Letters over drainage treatments (FD, free subsurface drainage; MD, managed subsurface drainage; ND, no subsurface drainage) represent differences in nitrate-N concentration within individual forage harvests using Fisher's Protected LSD (*P* ≤ 0.10).

CHAPTER 8

NITROGEN LOSS IN TILE DRAINAGE WATER FROM A FLOODPLAIN SOIL IN FORAGE PRODUCTION WITH MANAGED SUBSURFACE DRAINAGE

ABSTRACT

Forage production on soils with production restrictions, such as poorly-drained, floodplain soils may have the greatest potential to increase to meet future demands with the use of subsurface tile drainage. Expansion of tile drainage into forage production may have a deleterious effect on the environment in regard to N loading of surface waters. No research has evaluated whether managed subsurface drainage (MD) can reduce annual NO_3^--N loss in tile drainage water compared to free subsurface drainage (FD) in a forage production system. The objectives of the study were to 1) quantify the average concentration and annual loss of NO_3^--N in tile drain water from a poorly-drained, floodplain soil in winter rye and forage sorghum rotation with rotational cattle grazing and 2) determine whether MD could reduce annual NO_3^--N loss in tile water compared to FD. Annual NO_3^--N loss through tile drainage water ranged from 4 to 16 kg N ha^{-1} with FD over the three-year study. Annual flow-weighted mean concentration of NO_3^--N in the tile drainage water did not exceed 10 mg N L^{-1} with FD or MD. Managed drainage did not significantly ($P < 0.10$) reduce the annual tile water drained or NO_3^--N loss through the tile drainage water compared to FD. The inability to reduce annual tile water drained and subsequent NO_3^--N loss with MD compared to FD with a floodplain soil, as well as a relatively low overall potential for NO_3^--N loss through the tile drainage water with forage production indicates that the need or effectiveness of MD to reduced N

loading can vary due to the soil properties, landscape position, and crop production system.

INTRODUCTION

The United States beef cattle industry has increased 32% in value from 2002 to 2011 and is presently estimated to be worth $79 billion dollars (USDA, 2013). As livestock demand and production continue to rise, there is a greater need for increased forage production, as well as improved forage quality. Missouri ranks second in the number of cows in the United States (USDA, 2014). Forage production on soils with production restrictions, such as poorly-drained, floodplain soils may have the greatest potential increase to meet future demands.

Subsurface tile drainage is commonly used in agricultural fields throughout the Midwestern U.S. (> 20 million ha), primarily for continuous corn and corn-soybean rotations (Fausey et al., 1995), as a means to increase soil drainage and subsequent yields (Fausey et al., 1983; Kladivko et al. 2005; Nelson et al., 2009; Nelson et al., 2011; Nelson and Smoot, 2012; Nelson and Motavalli, 2013). However, extensive use of FD with agricultural production systems that require high N fertilizer inputs such as corn (Adviento-Borbe et al., 2010) has led to increased concern with N loading of surface waters (USEPA, 1992). Expansion of tile drainage into forage production with rotational cattle grazing may have a deleterious effect on the environment. Installation of free subsurface drainage (FD) has been found to facilitate movement of N out of agricultural soils and into surface waters (Fausey et al., 1995; Gilliam et al., 1999). Nitrate-N has a low potential for retention in soils and is readily transported with water movement through soil (Burkart and James, 1999). Increased water infiltration in soils with FD provides a more direct outlet for NO_3^--N to leave an agricultural field and enter surface waters (Fausey et al., 1995).

Aquatic ecosystems can be sensitive to anthropogenic additions of N as it is one of the most limiting nutrients in aquatic ecosystems. Nitrogen concentrations above natural levels in surface waters can result in hypoxia and eutrophication (USEPA, 1992), which involves rapid algae growth and depletes oxygen levels below what is required for higher forms of aquatic life (Burkart and James, 1999). Additionally, nitrate-N concentrations above 10 mg N L^{-1} in drinking water have been reported to cause health problems (USEPA, 2009).

The potential for NO_3^--N loss from tile drainage water can be related to the rate of N applied for production (Qi et al., 2011). Gast et al. (1978) reported that NO_3^--N loss through tile water increased from 19 to 129 kg N ha^{-1} as N rates increased from 20 to 448 kg N ha^{-1}. Therefore, extensive research evaluating the environmental impact of FD on N loading of surface waters has focused on agricultural practices that require high N fertilizer inputs such as row crop production. Annual NO_3^--N loss through tile drainage with high rates of applied N have ranged from 5 to 59 kg N ha^{-1} with continuous corn production (Gast et al., 1978; Hernandez-Ramirez et al., 2011), and 6 to 66 kg N ha^{-1} and 3 to 56 kg N ha^{-1} during the corn and soybean phases of a corn-soybean rotation, respectively (Jaynes et al., 2001; Randall and Vetsch, 2005; Hernandez-Ramirez et al., 2011; Qi et al., 2011). Annual flow-weighted mean concentration of NO_3^--N in tile water in relation to the 10 mg N L^{-1} drinking water quality standard has been reported to be 3 to 8 mg N L^{-1} greater (Jaynes and Colvin, 2006; Hernandez-Ramirez et al., 2011; Qi et al., 2011) and 9 mg N L^{-1} lower (Randall and Vetsch, 2005). Differences in the annual flow-weighted mean concentration of NO_3^--N in tile water among the studies were presumably due to differences in soil type, climate, and management.

Installation of tile drainage for forage production is not common, and N inputs required for forage are typically low relative to corn production. Therefore, research evaluating NO_3^--N loss in tile drainage water from forage sites is limited. Hernandez-Ramirez et al. (2011) reported that annual NO_3^--N loss through tile drainage water and the flow-weighted mean concentration was 2.5 kg N ha^{-1} and 2.7 mg N L^{-1} from a prairie grass field site when averaged over a six year study, respectively. Qi et al. (2011) reported annual NO_3^--N loss through tile drainage water and the flow-weighted mean concentration was 13.4 kg N ha^{-1} and 4.6 mg N L^{-1} from a perennial forage site, respectively. Lower annual NO_3^--N loading from prairie grass compared to row crop studies was likely due to lower N fertilizer inputs required for production. However, forage production sites that include cattle grazing may increase the potential for NO_3^--N loss through tile drainage water by facilitating the transfer of immobilized N in plant organic matter into inorganic N forms that are deposited on the field site and more readily available for leaching into tile drains.

Research has shown that up to 34% of the annual NO_3^--N loss through tile drainage water occurred during the non-cropping period (Drury et al., 2009). A managed subsurface drainage system (MD) is similar to FD, except for the addition of a water level control structure, which allows for the control of tile drainage flow through the adjustment of the outlet height. Managed drainage has been found to reduce annual water drained 30 to 50% compared to FD (Gilliam et al., 1979; Evans et al., 1995; Drury et al., 2009). Annual reductions in NO_3^--N loss in tile drainage water with MD compared to FD have ranged from 32 to 58% with corn production (Evans et al., 1990; Fogiel and Belcher, 1991; Drury et al., 2009). The ability to reduce annual NO_3^--N loss through tile drainage water with MD compared to FD was derived from reducing the amount of water drained during the non-cropping period (Evans et al., 1995; Fausey et al., 1995).

Research comparing NO_3^--N loss in tile drainage water between FD and MD has been limited to field crops such as corn and soybeans. No research has evaluated whether MD can reduce annual NO_3^--N loss in tile drainage water compared to FD in a forage production system. The objectives of the study were to 1) quantify the average concentration and annual loss of NO_3^--N in tile drain water from a poorly-drained, floodplain soil in a winter rye and forage sorghum rotation with rotational cattle grazing and 2) determine whether MD could reduce annual NO_3^--N loss in tile water compared to FD.

MATERIALS AND METHODS

Site Description and Experimental Design

The three-year study was initiated in September of 2010 at the University of Missouri's Greenley Memorial Research Center (40° 1' 17" N, 92° 11' 24.9" W) near Novelty, MO. The soil was a Blackoar silt loam (Fine-silty, mixed, superactive, mesic Fluvaquentic Endoaquolls) which is a floodplain soil. Soil samples (composite of three samples) were taken from each plot at depths of 0 to 0.3, 0.3 to 0.6, and 0.6 to 0.9 m in the fall of 2011, 2012, and 2013 with a Giddings Probe (Giddings Machine Company, Windsor, CO). Soil properties were analyzed using standard soil test procedures for Missouri (Nathan et al., 2006) (Table 8.1). Soil NH_4^+-N and NO_3^-N concentration was converted from mg kg^{-1} to kg ha^{-1} based on soil bulk density measurements taken at the depths of 0-0.3, 0.3-0.6, and 0.6-0.9 m at the field site in 2013. There were two replications and plot sizes were 37 by 91 m and 37 by 305 m in replications one and two, respectively. Subsurface tile drainage systems, including the water level control structures were installed in August 2009. The subsurface tile drains were installed at a 0.91 m depth with 18.3 m spacing, and ran the length of the plots. In each replication, there were FD and MD treatments.

The experiment field site was in a winter rye (*Secale cereale* L.) and brown mid-rib sorghum [*Sorghum bicolor* (L.) Moench] rotation in combination with beef cattle (*Bos tauurus* Aberdeen angus) rotational grazing system. The field site was divided into sections perpendicular to the plots in order to maintain a uniform stocking rate (19 head ha^{-1}) across the entire field site. Vertical tillage (Case IH 330, Racine, WI) was done directly before winter rye, 'VNS', was broadcasted at 111 kg seed ha^{-1} with a fertilizer cart. Sorghum cultivars (NUTRI+PLUS in 2011, TD7000 in 2012, and Trophy II in 2013) were NT, seeded in the summer at 18 to 23 kg ha^{-1} with 76 cm spacing in 2011 and 2012, and 38 cm spacing in 2013. Management information including planting dates, N fertilizer application, and water level management with MD are presented in Figure 8.1 and 8.2. Daily precipitation values were obtained from the nearby Greenley Memorial Research Center weather station (Campbell Scientific, Logan, UT).

Water Sample Collection, Flow, and Nitrate Loss Measurements

Submerged area/velocity sensors (Sigma, Hach, Loveland, CO) were used to measure water height every five minutes in the water-level control structures during spring through summer months. Pressure transducers (American Sensor Technologies, Mount Olive, NJ) measured water height every five minutes in the water-level control structures during the winter months. Additionally, during periods of tile flow in 2012 and 2013, daily water height readings were recorded manually in the water-level control structures using a Little Dipper field instrument (Heron Instruments, Dundas, Ontario), as a means of data quality assurance. Flow rates were obtained by subtracting the height of the slides from the water height readings in the control structures and then using the equation:

$$\text{Flow rate (L m}^{-1}\text{)} = 1.4533 * \text{Flow depth (cm)}^2$$

The equation, obtained through laboratory testing (Chun and Cooke, 2008), was specific to the dimensions of the water-level control structures and angle of the top weir slides used in the study. Flow rates were then divided by the area drained to obtain measurements of flow over time and area, which were extrapolated to estimate the total daily flow from each plot.

Portable automated water samplers (Sigma 900MAX, Hach, Loveland, CO) collected water samples every six hours when flow was present. Water samples were combined into daily composite samples. During winter, water samples were manually collected approximately every other day when flow was present. Tile drainage water samples were stored in a refrigerator (5 ^{o}C) and filtered (1.5 µm, 934-AH, Whatman Glass Microfiber, General ElectricBio-Sciences, Pittsburgh, PA) prior to being analyzed for NO_3^--N concentration (10-107-04-1-F Quick Chem) using an automated ion analyzer (Lachat Quik Chem 8000, Loveland, CO).

Statistical Analysis

Soil N concentration, water drained, NO_3^--N loss, and flow-weighted mean concentration of NO_3^- in the tile drainage water by study year were statistically analyzed for treatment effects using ANOVA and PROC GLM with SAS v9.3 (SAS Institute, 2013). Fall soil NO_3^--N concentration was only significantly ($P < 0.05$) affected by the main effects of depth and year. Fall soil NH_4^+-N concentration was significantly ($P \leq 0.05$) affected by the interaction of tile drainage systems and year. Soil depth had no effect on the soil NH_4^+-N concentration in the fall. Cumulative water drained, NO_3^- loss, and annual flow-weighted mean concentration of NO_3^- in the tile drainage water were not significantly ($P \leq 0.10$) affected by tile drainage systems over the three-year study. Significant differences in treatment means were determined using Fisher's Protected LSD.

RESULTS AND DISCUSSION

Precipitation

Cumulative precipitation among the three study years (approximately September through August) was generally similar. The range in cumulative precipitation was 795 mm (2011-2012), and 964 mm (2012-2013) (Fig. 8.1). However, the distribution of precipitation varied over the three-year study. In 2010, high precipitation occurred in September, which was at least 141% greater than 2011-2013. From October through March, the period in which tile flow was usually restricted with MD, precipitation totaled 155 mm (2010-2011), 377 mm (2011-2012), and 332 mm (2012-2013). From April through July, the period of time when tile flow was usually not restricted with MD, precipitation totaled 485 mm in 2011, 258 mm in 2012, and 595 mm in 2013. High intensity precipitation events in April and June of 2013 resulted in brief periods of flooding. Low precipitation in combination with high air temperature (data not presented) generally resulted in dry soil conditions during the months of July through September of the three-year study.

Soil Nitrogen Concentration

Soil NO_3^--N concentration in the fall was significantly ($P \leq 0.05$) greater at the 0 to 0.3 m depth (74 kg N ha^{-1}) than at the 0.3 to 0.6 and 0.6 to 0.9 m depths (21.5 to 24.3 kg N ha^{-1}) when averaged over tile drainage systems and years (Table 8.2). Additionally, soil NO_3^--N concentration was significantly ($P \leq 0.05$) greater in 2011 (62.3 kg N ha^{-1}) and 2012 (46.7 kg N ha^{-1}) compared to 2013 (30.8 kg N ha^{-1}) when averaged over tile drainage systems and depths. Soil NH_4^+-N concentration in the fall was significantly ($P \leq 0.05$) greater in 2011 with MD compared to FD in 2011 and FD and MD in 2012 and 2013. High soil N concentration observed due to year (2011) with NO_3^--N and tile drainage system/year (MD in 2011) with NH_4^+-N, was likely a function of the amount of N applied in combination with reduced tile flow compared to 2012 and 2013.

Tile Water Drained

Tile drainage flow was highly responsive to precipitation events over the three-year study (Fig. 8.2). The amount of tile water drained with FD accounted for 6, 12.2, and 19.4% of the precipitation received in the 2010-2011, 2011-2012, and 2012-2013 study years, respectively. Managed drainage did not significantly ($P \leq 0.10$) reduce the amount of tile water drained over the three-year study. This result was counter to previous research on upland soils which reported that MD reduced annual water drained 30 to 50% compared to FD (Gilliam et al., 1979; Evans et al., 1995; Drury et al., 2009). The inability to reduce the amount of tile water drained with MD compared to FD was likely a function of the inherent variability in tile drain flow at the field site and similar rates of tile flow with MD compared to FD regardless of the tile outlet height in the water level control structures. These responses in tile flow were presumably due to the physical properties of the soil, low landscape position, and crop production system.

Nitrate-N Loss in Tile Drainage Water

Managed drainage did not significantly ($P \leq 0.10$) reduce NO_3^--N loss compared to FD over the three-year study (Fig. 8.2). Previous research has reported 32 to 58% reductions in annual NO_3^--N loss in tile drainage water with MD compared to FD, which was primarily due to reduced annual tile drainage flow with MD (Evans et al., 1990; Fogiel and Belcher, 1991; Drury et al., 2009). Therefore, the lack of a reduction in annual tile water drained with MD compared to FD likely accounted for similar annual NO_3^--N loss through the tile drainage water among MD and FD over the three-year study.

Concentration of NO_3^--N in the tile water was typically under 5 mg N L^{-1} over the three-year study (Fig. 8.2). However, for brief periods the concentration of NO_3^--N in the tile water increased as high as 33 mg N L^{-1} from September through November in 2010-2012, and 22 mg N L^{-1} from February through April in 2012 and 2013. Elevated NO_3^--N concentration in the tile drainage water over March through April may have been partially due to the increased frequency of cattle grazing and subsequent manure inputs over those months. Loss of NO_3^--N through tile drainage water has been reported to be similar between spring application of manure and ammonium nitrate fertilizer (Hernandez-Ramirez et al., 2011).

Nitrate-N loss through tile drainage water over a study year ranged from 4 to 16 kg N ha^{-1} with FD over the three-year study (Fig. 8.2). This was similar to previous FD research that reported annual NO_3^--N loss through the tile drainage water ranged from 2.5

to 14.3 kg N ha^{-1} in a forage production system (Hernandez-Ramirez et al., 2011; Qi et al., 2011). Annual NO_3^--N loss through tile drainage water from corn-soybean rotations has been reported to range from 3 to 66 kg N ha^{-1} (Jaynes et al., 2001; Randall and Vetsch, 2005; Hernandez-Ramirez et al., 2011; Qi et al., 2011). Reduced annual NO_3^--N loss through tile drainage water with forage production compared to corn-soybean production may be due to reduced N inputs and continuous plant growth throughout the year.

Flow-Weighted Mean Concentration of Nitrate-N in Tile Drainage Water

Annual flow-weighted mean concentration was similar among FD and MD over the three-year study (Fig. 8.3). The annual flow-weighted mean concentration of NO_3^--N in the tile drainage water ranged from 3.5 to 9.5 mg N L^{-1} over the three-year study. Similarly, low annual flow-weighted mean concentration of NO_3^--N in the tile drainage water (2.7 to 4.6 mg N L^{-1}) was reported in two previous research studies on forage production. Since annual flow-weighted mean concentrations of NO_3^--N did not exceed the 10 mg N L^{-1} drinking water standard (USEPA, 1992), tile draining floodplain soils for forage production with cattle grazing may have a minimal impact on human health regarding drinking water quality.

CONCLUSIONS

Managed drainage did not reduce annual tile water drained and NO_3^--N loss through the tile drainage water compared to FD in the Blackoar silt loam, floodplain soil in winter rye-sorghum forage production system with cattle grazing. The inability to reduce the amount of tile water drained with MD compared to FD was likely a function of the inherent variability in tile drain flow at the field site and similar rates of tile flow with MD compared to FD regardless of the tile outlet height in the water level control structures. These responses in tile flow were presumably due to the physical properties of the soil, low landscape position, and the crop production system. However, annual NO_3^--N loss through the tile drainage water with FD was relatively low compared to most corn and soybean production systems. Annual flow-weighted mean concentration of NO_3^--N in the tile drainage water never exceeded the 10 mg N L^{-1} drinking water standard. Therefore, the need for MD to reduce annual N loading of surface waters due to the presence of tile drainage may not be necessary with floodplain soils in annual forage production.

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Table 8.1. Select soil chemical properties from fall soil sampling at depths of 0 to 0.3, 0.3 to 0.6, and 0.6 to 0.9 m in 2011, 2012, and 2013. Data were averaged over drainage treatments in the fall of 2011, 2012, and 2013.

							Exchangeable ($1\ M\ NH_4AOc$)				
Year	Depth	pH	Organic matter	Neutral acidity	CEC†	Bray I P	Ca	K	Mg	NH_4^+-N	NO_3^--N
	-- m --	$0.01\ M\ CaCl_2$	g kg^{-1}	--$cmol_c\ kg^{-1}$ --		mg kg^{-1}	--------------------kg ha^{-1}				---------------------
2011	0-0.3	5.2	23	4.5	14.6	31.4	3637	201	466	50.2	99.5
	0.3-0.6	4.6	15	5.5	14.5	45.4	2994	181	563	73.6	37.4
	0.6-0.9	4.5	19	7.0	16.9	35.3	3247	232	628	37.1	49.9
2012	0-0.3	5.4	28	3.9	14.5	35.6	3916	241	428	20.7	101.9
	0.3-0.6	4.8	17	6.3	13.5	29.4	2476	171	406	16.7	30.4
	0.6-0.9	4.3	11	10.4	22.5	16.5	3767	233	931	16.5	7.8
2013	0-0.3	5.2	23	5.3	15.8	44.2	3797	262	459	16.3	20.7
	0.3-0.6	4.5	10	7.6	16.0	31.9	2769	162	523	16.6	4.9
	0.6-0.9	4.4	10	7.6	17.1	18.2	3084	172	644	20.5	6.6

† Abbreviations: CEC = cation exchange capacity; Neutral = neutralizable.

Table 8.2. Fall soil NO_3^--N concentration presented by depths (averaged over tile drainage systems and year) and year (averaged over depths and tile drainage systems). Fall soil NH_4^+-N concentration was presented by tile drainage systems and year (averaged over depths).

					Soil NH_4^+-N	
Depth	Soil NO_3^--N	Year	Soil NO_3^--N	Year	FD	MD
--- m ---	--- kg N ha^{-1} ---		--- kg N ha^{-1}---		---- kg N ha^{-1} ----	
0-0.3	74.0	2011	62.3	2011	27.2	80.1
0.3-0.6	24.3	2012	46.7	2012	17.8	18.2
0.6-0.9	21.5	2013	10.7	2013	18.9	16.8
LSD (0.05)	30.8		30.8	LSD (0.05)	------- 25.6 ---------	

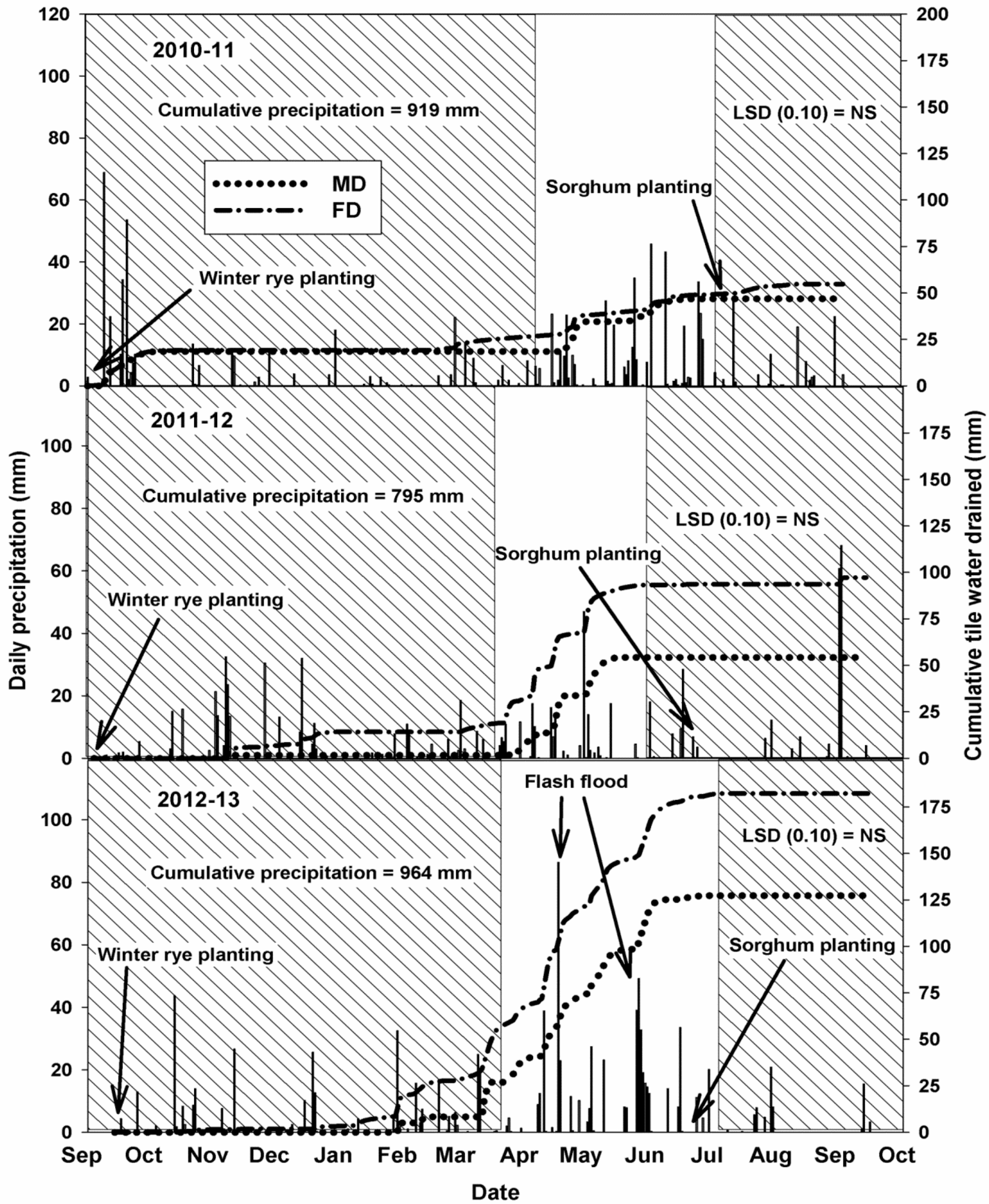

Figure 8.1. Daily precipitation (bars) and cumulative tile water drained (lines) by tile drainage system (FD = free drainage system and MD = managed drainage system) and years. The start of each study year corresponds to the planting of winter rye. Shaded areas represent the period of time that MD treatments were in managed drainage mode. NS = not significant.

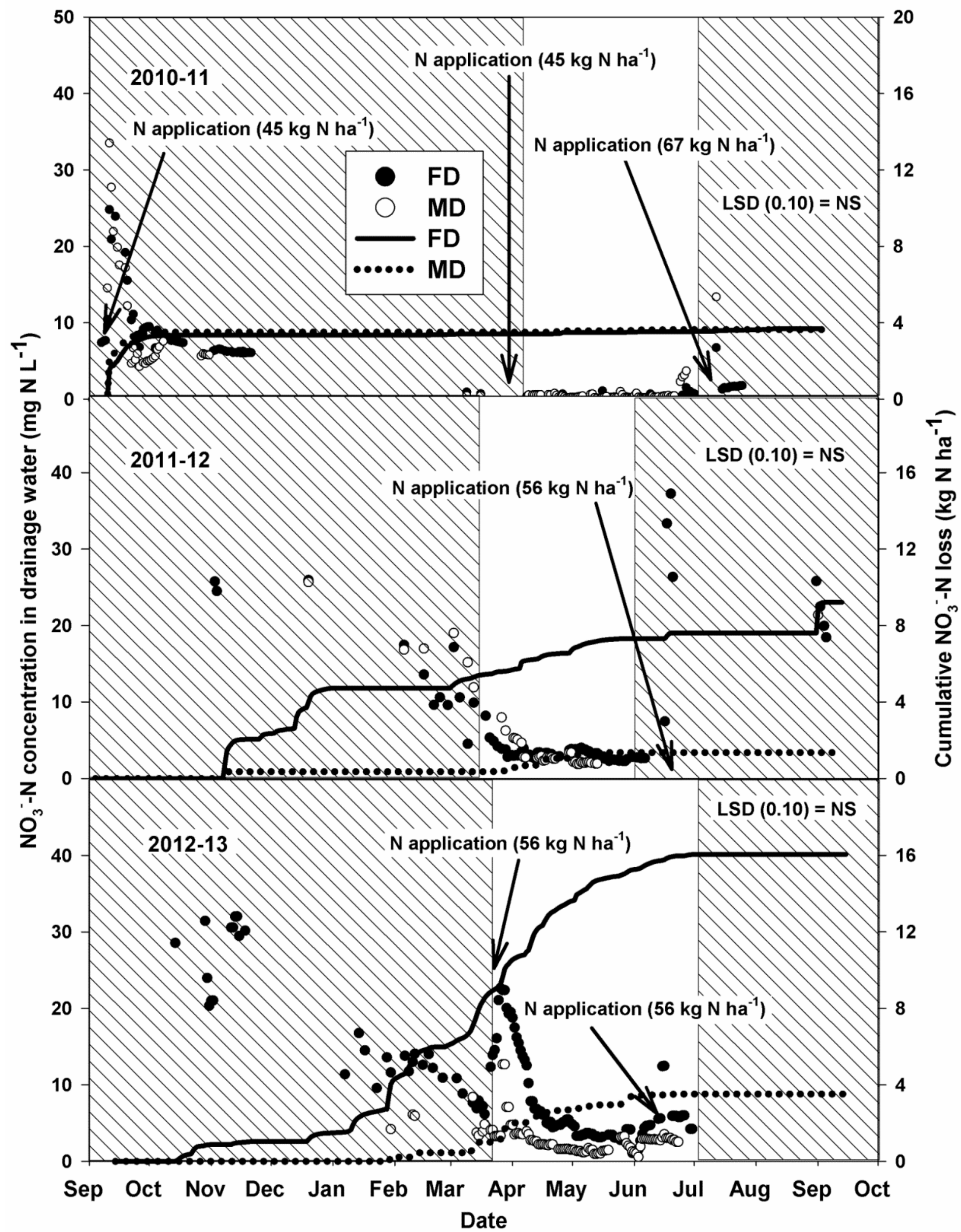

Figure 8.2. Daily concentration of nitrate-N in tile drainage water (circles) and cumulative nitrate-N loss (lines) by tile drainage system (FD = free drainage system and MD = managed drainage system) and years. The start of each study year corresponds to the planting of winter rye. Shaded areas represent the period of time that MD treatments were in managed drainage mode. NS = not significant.

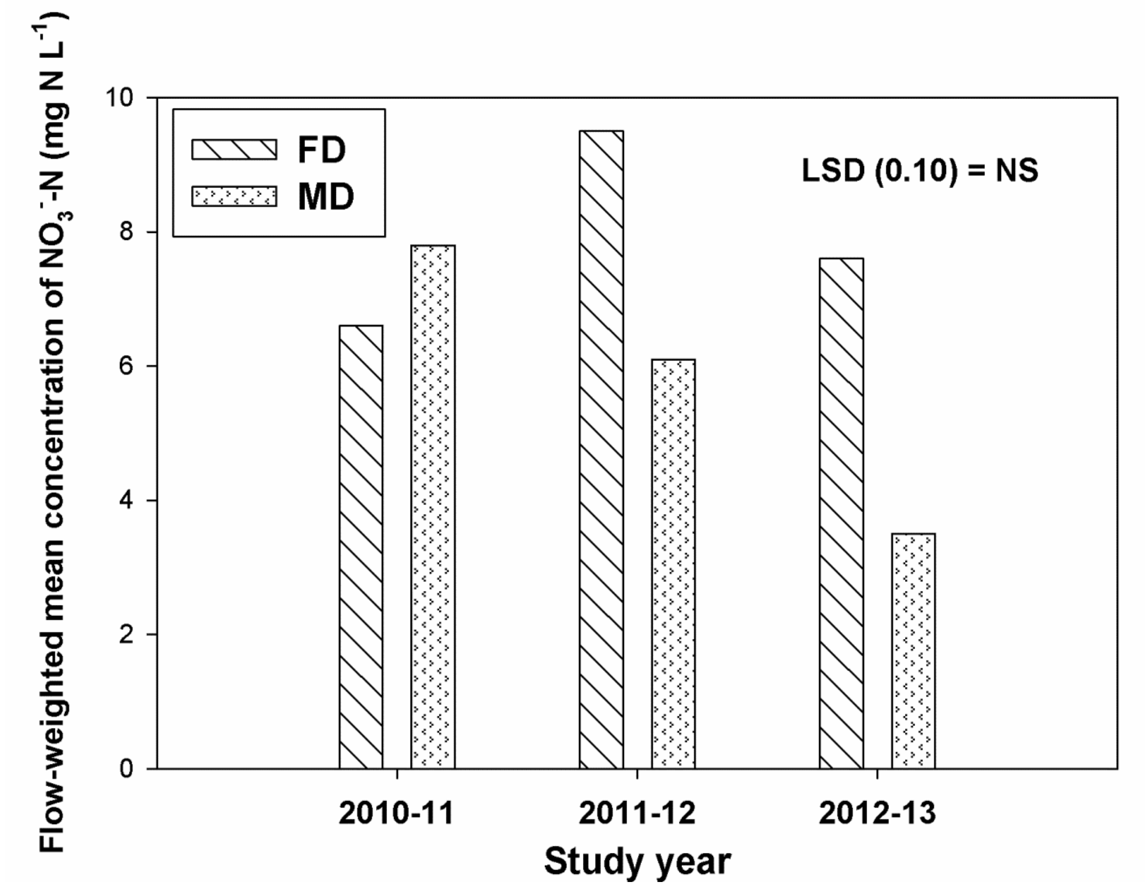

Figure 8.3. Flow-weighted mean concentration of NO_3^--N in the tile water among tile drainage systems (FD = free drainage system and MD = managed drainage system) by years. The start of each study year corresponded to a single winter rye and sorghum rotation (approximately one year). NS = not significant.

CHAPTER 9

OVERALL CONCLUSIONS

This research provided a comprehensive opportunity to determine the effectiveness of managed drainage (MD) systems and N fertilizer management across a range of cropping systems, soil properties, landscape positions and differences in climate during several growing seasons in northeastern Missouri. Both the production and environmental effects of these systems were evaluated. Since subsurface tile drainage systems have not been commonly installed in Missouri in the past, the research results provide important information to producers considering use of either free drainage (FD) and managed drainage (MD) systems. In addition, the research results may assist public agencies when considering the environmental impact of these systems and possible subsidies for their installation in Missouri to reduce potential water and air pollution caused by agricultural management practices.

Crop yield response, tile water drained, and subsequent NO_3^--N loss through tile drainage water varied due to the tile drainage systems [free drainage (FD), managed drainage (MD), and no drainage (ND)], N fertilizer source [non-coated urea (NCU) and polymer-coated urea (PCU)], differences in soil properties between the soil series (Putnam silt loam, Wabash silty clay, and Blackoar silt loam), landscape position (upland and bottomland), and crop production system (continuous corn and forage). The four years (2010-2013) in which the studies took place could generally be described as wet in 2010 and dry in 2011-2013. However, the crop response to excessive or lack of precipitation did vary slightly among the tile studies due to the soil properties, landscape position, and crop production system.

Corn grain yield response to the presence of tile drainage or use of PCU was limited throughout the four-year studies on the upland, Putnam and bottomland, Wabash soil. Excessive soil moisture due to poor internal drainage of these soils is typically the most limiting factor affecting corn grain yields. Contrary to the norm, soil water deficit was likely the greatest limiting factor affecting corn grain yields over the four study years, due to abnormally dry conditions experienced over a majority of the growing seasons. Therefore, the expected increase in corn yields in the poorly-drained upland and bottomland soils with the presence of tile drainage was likely minimized.

Corn grain yields with the presence of tile drainage amended with PCU or NCU compared to ND with PCU were similar, but the yields were 21% greater than ND with NCU with the upland, Putnam soil, when averaged over the four years. This result indicated that in the absence of drainage, wet spring conditions resulted in a high potential to lower corn grain yields if a controlled-released N fertilizer was not applied. In contrast, PCU had no effect on corn grain yields in the presence or absence of drainage with the bottomland, Wabash soil. However, corn grain yields increased 13% with the presence of drainage in 2012, which was dry throughout most of the growing season. Lack of a corn yield response with PCU compared to NCU with the bottomland, Wabash soil may have been due to later N fertilizer application and planting dates compared to the tile drainage study on the upland, Putnam soil which reduced the potential for environmental N loss due to drier soil conditions. Additionally, increased corn yield production with the presence of drainage in a generally dry growing season at the bottomland, Wabash soil tile site was likely due to improved root development in the spring with the lowering of the water table, which improved plant-water use efficiency during the dry summer months compared to ND.

Increased corn yields with application of PCU compared to NCU are typically derived from the greater N availability for corn uptake due to reduced environmental N loss. Dry conditions over the late spring through summer months likely limited overall environmental N loss, corn N uptake, and yield, which resulted in N build up in the soil and subsequent carry over into the following seasons. However, wet spring conditions did result in a small amount of gaseous N (ammonia and nitrous oxide) loss prior to drought conditions. Measured only at the upland, Putnam field site, PCU reduced soil ammonia volatilization and N_2O emissions compared to NCU over growing seasons due to the controlled release properties of PCU when both PCU and NCU were incorporated. However, combined N loss through soil ammonia volatilization and N_2O emissions typically accounted for less than 8% of applied N fertilizer and likely was not of agronomic significance when factored in with high residual soil N concentration. However, soil N_2O emissions may have been of environmental significance due to N_2O's high global warming potential.

In contrast to the corn production systems, the presence of tile drainage in an annual forage system increased total annual biomass yield (winter rye plus sorghum), when averaged over four years. The contrasting response among production systems was likely due to forage plant growth occurring year-round compared to just the spring and summer months when growing conditions for corn were usually dry and tile drainage flow was minimal. A majority of the increase in annual biomass yield was derived during the winter rye phase of the winter rye-sorghum rotation. The winter rye growth period occurred over the winter and early spring when air temperature was low and precipitation was high enough to induce saturated soil conditions in the absence of tile drainage. Limited effects on sorghum biomass yields with the presence of tile drainage were due to limited precipitation and tile flow over the summer growth period.

Managed drainage did not significantly increase crop yields compared to FD, regardless of the soil properties, landscape position, or crop production system. This result was counter to some previous research and the theory that MD can increase yield compared to FD in dry years due to the added ability to conserve soil water and increase plant water uptake. Flash droughts that extended over long periods during the period of the research likely negated any potential for MD to conserve soil water compared to FD, as precipitation was required after putting MD into controlled drainage or MD mode in order to increase plant available water compared to FD. Increased corn and forage yields with MD compared to FD maybe be possible in growing seasons with shorter drought periods.

The presence of tile drainage likely reduced the occurrence of saturated soil conditions compared to ND in every soil series and landscape position. The magnitude and temporal response in tile drainage flow varied due to the soil properties, landscape position, and crop production system. Tile drainage flow at the tile field sites with FD accounted for 13 to 20% of the annual precipitation with the upland, Putnam silt loam soil; 93 to 145% with the bottomland, Wabash silty clay soil; and 6 to 19% of the annual precipitation with the bottomland, Blackoar silt loam soil. The high tile drainage flow in relation to the precipitation received with the Wabash silty clay soil was likely due to the relatively low landscape position and an elevated water table which resulted in tile flow almost year-round except for the dry summer months. The Blackoar silt loam soil was similar to the Wabash soil in that it was also a bottomland soil; however, the water table did not contribute to tile drainage flow. Tile drainage flow did not occur with MD while in MD mode with the upland, Putnam silt loam soil, but did occur at times in both of the bottomland soils. The contrasting response of tile drainage flow between the upland and bottomland soils was likely a function of the claypan layer in the upland soil and the natural water table which likely contributed to the tile drainage flow in the bottomland soils.

The ability to reduce the annual amount of tile water drained with MD compared to FD varied due to the soil properties, landscape position, and cropping production system. In two of four years, MD reduced the annual tile drained water by 73 to 76% in the upland, Putnam soil in corn production by restricting tile flow during the non-cropping period. Reduction in the annual amount of tile water drained with MD compared to FD was 52% with the bottomland, Wabash soil in corn production, averaged over three years. In contrast to the upland soil, tile flow in the bottomland soils occurred at times during the non-cropping period with MD, but less frequently than with FD. These annual reductions in the amount of tile water drained with MD compared to FD were similar to greater than what had previously been reported in research on upland soils in corn production. Limited tile flow during the growing season in combination with no tile flow during the non-cropping period with MD resulted in higher than expected reductions in the annual amount of water drained with MD compared to FD. Managed drainage did not reduce the annual amount of tile water drained compared to FD with the bottomland, Blackoar soil in annual forage production. Contrary to the upland, Putnam and bottomland, Wabash soils in corn production, the bottomland, Blackoar soil had inherent variability in tile drain flow across the field site, as well as similar rates of tile flow with MD compared to FD regardless of the 0.6 m higher tile outlet height in the water level control structures.

Annual NO_3^--N loss through the tile drainage water with FD was 7 to 30 kg N ha^{-1} for the upland, Putnam soil and 30 to 90 kg N ha^{-1} with the bottomland, Wabash soil in continuous corn production, respectively. It is not uncommon to lose 30 kg NO_3^--N ha^{-1} annually through tile drainage water flow in soils with continuous corn production. However, annual NO_3^--N loss through tile drainage water rarely has been shown to exceed 60 kg N ha^{-1} in upland soils in corn production. High annual NO_3^--N loss through the tile drainage water with the bottomland, Wabash soil in corn production was primarily due to greater flow rates than what is commonly observed in upland soils, which was likely due to the low landscape position and a naturally elevated water table that contributed to the tile flow. The annual NO_3^--N loss through the bottomland, Blackoar soil with FD and annual forage production ranged from 4 to 16 kg N ha^{-1}. The typically lower annual NO_3^--N loss through the tile drainage water at the forage production site compared to the corn production sites was likely a function of lower annual N fertilizer inputs and the year-round potential for plant N uptake.

Annual flow-weighted mean concentration of NO_3^--N in the tile drainage water exceeded the 10 mg N L^{-1} drinking water standard in two of the four years with the upland, Putnam soil in corn production. In contrast, flow-weighted mean concentrations of NO_3^--N in the tile drainage water did not exceed 10 mg N L^{-1} in both bottomland soils in corn and forage production. Low flow-weighted mean concentrations observed in two of the three sites were likely a function of the water table contributing to greater tile flow in the corn production site, and low N fertilizer inputs at the forage production site. However, it is important to note that flow-weighted mean concentration should not be used as the sole indicator of the environmental or health impact from tile drainage practices. High annual flow-weighted mean concentrations of NO_3^--N in two of the four years (23.6 to 27.2 mg N L^{-1}) with the upland, Putnam soil were typically due to low annual tile drainage flow and subsequently had relatively low annual NO_3^--N loss (5 to 18 kg N ha^{-1}).

The ability to reduce annual NO_3^--N loss through tile drainage water with MD compared to FD is primarily derived from reduced tile drainage flow during periods when drainage was not advantageous to crop production. Managed drainage reduced the annual NO_3^--N loss through the tile drainage water compared to FD in upland and bottomland soils in corn production. Annual NO_3^--N loss through the tile drainage water was not reduced with MD compared to FD in the bottomland soil in forage production, as annual tile water drained was similar between MD and FD. However, annual NO_3^--N with FD at the forage production site was similar to less than what was observed with MD with the upland and bottomland soils in corn production.

Overall, installation of tile drainage systems were effective in improving the soil drainage of the poorly-drained soils across landscape positions and subsequently minimizing the presence of saturated soil conditions compared to ND. Dry conditions over much of spring and summer months during the four study years lowered the overall yield potential of corn and forage sorghum and minimized the yield benefits of tile drainage. If precipitation events were similar to or greater than what was common for the region, a more consistent increase in crop yields with the presence of drainage compared to ND would likely have occurred, similar to what has been observed in previous research. Use of controlled-release N fertilizer in conjunction with tile drainage may only increase corn yields in abnormally wet growing seasons compared to an NCU application. The presence of tile drainage can minimize the occurrence of saturated soil conditions and subsequently lower the potential environmental N loss and the need for controlled-release N fertilizer such as PCU. Regardless of the abnormally dry conditions over the four study years, MD was effective in reducing annual NO_3^--N through the tile drainage water in both an upland and bottomland soils in corn production. However, the inability to reduce annual tile water drained and subsequent NO_3^--N loss through tile drainage water with MD compared to FD in the bottomland, Blackoar soil, as well as a relatively low overall potential for NO_3^--N loss through the tile drainage water with forage production indicates that the need or effectiveness of MD to reduced N loading can vary due to the soil series and crop production system. Although use of a controlled-release fertilizer in conjunction with MD did not reduce annual NO_3^--N through the tile drainage water over the four study years, wetter growing season conditions similar what is common for the region could result in greater NO_3^--N through the tile drainage water in the spring. Therefore, PCU in combination with MD could reduce NO_3^--N through tile drainage water compared to NCU during the spring months when tile flow is not restricted and subsequently reduce annual NO_3^--N loss through tile drainage water.

In the future, research studies would need to be conducted over years with and without precipitation similar to greater than what is common for the region to fully understand crop and environmental response to tile drainage systems and controlled-release N fertilizers with different soil properties and landscape positions. This research demonstrated that NO_3^--N loss through tile drainage water with MD primarily occurred during the spring period when flow was not restricted. Therefore, there may be potential to further reduce the environmental impact of tile drainage by combining MD with other management practices which could reduce loss of applied N during the spring such as application of physical or chemical controlled-release N fertilizers and split N fertilizer applications.

A majority of research that has evaluated the environmental impact of tile drainage has focused on water quality. Recent concern with climate change and the impact that agriculture has on greenhouse gas emissions have become a sensitive issue. Tile draining poorly-drained soils may actually reduce emission of greenhouse gases, such as N_2O. However, due to a lack of ND controls in most tile drainage research, there is no information available on the impact of tile drainage on soil N_2O emissions. Future design of tile drainage studies should include ND controls in order to evaluate whether tile draining agricultural fields can lower the environmental impact in regard to greenhouse gas emissions.

VITA

Patrick Nash was born in Minnesota, on June 8, 1986. After finishing high school in 2004, he enrolled at the University of Minnesota, Twin Cities and received a B.S. in environmental science with a focus in soil science in 2008. He received a M.S in soil science from the University of Missouri in December 2010, and a Ph.D. in soil science from the University of Missouri in May 2014.