DEMONSTRATION OF ANAEROBIC DIGESTION CENTRATE AS A NITROGEN & WATER SOURCE FOR CORN GRAIN PRODUCTION

BY

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THESIS

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ABSTRACT

In this study, a method to deliver subterreanean nitrogen and water as a strategy to benefit both corn producers and wastewater treatment plants (WTPs) was demonstrated for two growing seasons in 2013 and 2014. Subirrigation (SI)/drainage tiles were installed (approximately 60 cm) and used to deliver either anaerobic digestion (AD) centrate ("SICW") or dissolved urea ("SIUW") to growing corn plants. These plots were compared to topically applied urea without SI ("Non-SI U") and controls ("No N" in 2013 and "Base N" in 2014).

The first objective of the study was to evaluate corn grain yield and plant nitrogen uptake with AD centrate or urea through SI. AD centrate or urea was added through the SI pipes in 3 to 5 events during the late vegetative and early reproductive phases of 2013 and 2014. Results indicated that, in 2013, among low rate nitrogen treatments (SICW N+ and SIUW N+), SI enhanced average grain yield by 9% ($p = 0.05$) and nitrogen uptake by 18% ($p < 0.01$) compared to unfertilized controls (7803 kg grain/ha and 170 kg N/ha). A high rate nitrogen treatment (SICW N++) enhanced average grain yield by 18% compared to the Champaign county average of 9010 kg grain/ha. Low rate nitrogen SI treatments enhanced average grain yield by 8% ($p = 0.18$) and nitrogen uptake by 8% ($p = 0.06$) compared to low rate nitrogen Non-SI U treatment plots (7905 kg grain/ha and 185 kg N/ha). In 2014, a wet growing season, among low rate nitrogen SI treatments, SI enhanced average grain yield by 12% ($p = 0.07$) and nitrogen uptake by 10% ($p = 0.06$) compared to controls which received a base nitrogen application (Control Base N) of 140 kg N/ha (4590 kg grain/ha and 110 kg N/ha). Low rate nitrogen SI treatments enhanced average grain yield by 15% ($p = 0.22$) compared to low rate nitrogen Non-SI U treatment plots (4840 kg grain/ha). Among high rate nitrogen SI treatments (SICW N++ and

SIUW N++), SI enhanced average grain by 26% ($p < 0.01$) and nitrogen uptake by 27% ($p < 0.01$) compared to controls with a base nitrogen application. High rate nitrogen SI treatments enhanced average grain yield by 14% ($p = 0.08$) compared to high rate nitrogen Non-SI U (Non-SI U N++) treatment plots (5100 kg grain/ha).

The second objective was to assess nitrogen and water movement away from an SI pipe in unsaturated soil conditions. A soil profile box was built and centrate was added. Both soil moisture and NH_4-N were measured after 48 hours. Water moved uniformly throughout the soil matrix compared to NH_4-N—the standard deviation of 7 measured points' soil water concentration was 13% of the average, compared to the standard deviation of 7 measured points' NH_4-N concentration which was 174% of the average.

In summary, the results indicate that delivering centrate and water through SI is an effective strategy for late vegetative nitrogen and water delivery when N uptake is highest (Bender, Haegele et al. 2012); however, the physical and chemical mechanisms through which water and nitrogen move through the soil vary—as such, the beneficial effect that they can each have on grain yield and nitrogen uptake will change depending upon climatic conditions.

ACKNOWLEDGMENTS

When I took on this opportunity two and a half years ago, I was overwhelmed and intimidated by the task before me. To have finally reached this point despite the variety of challenges, I know I could not have done it alone; as such, the following persons deserve special recognition:

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CHAPTER 1: INTRODUCTION

A growing world population and the effects of climate change are putting an increasing demand on the Earth's natural resources—resources essential for clean drinking water and irrigation to enhance food, fuel, and fiber production. Climate change is expected to make precipitation patterns even more extreme in frequency and quantity (O'Gorman and Schneider, 2009). For that reason, a broadly-applicable and sustainable solution is needed which can significantly mitigate these effects of climate change—specifically on agriculture and municipalities.

Integrating nitrogen and water utilization at farms with nitrogen and water processing at municipal wastewater treatment plants (WTPs) can provide an attractive solution. Agricultural producers, often located on the fringes of WTPs, carefully manage their costly nitrogen and finite water resources to maximize corn yield. At the WTP, nitrogen and water, centrally collected in human waste products, are processed taking little to no advantage of their nutrient and irrigation value to plants.

A solution that delivers nitrogen and water under the surface, subirrigation-controlled drainage (SI-CD, hereafter, referred to as "SI"), in the form of a high strength wastewater produced in the WTP's anaerobic digestion process, known as centrate, will be investigated in this study. SI is a relatively new, durable, and adaptable irrigation system over a variety of topographies and weather conditions that costs approximately $7,000 per hectare (unpublished data, 2003. Anchor, IL: Agrem, LLC).

Wastewater is often applied to growing plants through slow rate land application (Crites, 2001); however, due to low inorganic nitrogen concentration (30 mg/L $NH_4 + NO_3$-N) (unpublished data, 2012. Urbana, IL: Urbana-Champaign Sanitary District) usage would require prohibitive, or at least inhibitory, volumes of water to satisfy corn nitrogen needs. Anaerobic digestion is an increasingly utilized strategy to manage waste solids at WTPs which generates high-nitrogen dewatering liquor known as centrate. This centrate's NH_4-N load can constitute 10 to 20% of the total WTP nitrogen quantity when it is redirected to the start of its treatment (Bartrolí, Garcia-Belinchon et al., 2013).

In this study, centrate was delivered to growing corn plants using SI in order to demonstrate this solution's potential grain yield benefit to farmers and reduced N treatment costs for WTP managers. Corn plants were grown during two growing seasons (2013 and 2014) on the University of Illinois Agricultural & Biological Engineering Research Farms using a SI system designed and installed with the aide of Mr. Robert & Dr. Jeremy Meiners of the Agrem, LLC (Anchor, Illinois). Centrate and additional advisement were provided by the UCSD NE (Urbana-Champaign Northeast) WTP. Field management and equipment was provided by farm managers, Tim Lecher and Ron Estes.

Farmers who need to pay for synthetic nitrogen, want to protect corn from damages during drought, and experience social pressure from those concerned with agricultural contributions to Gulf of Mexico eutrophication, UCSD NE and other WTPs can benefit from this work.

Farmers currently pay approximately $700/ton NH_3 (12/09/14 fertilizer dealer near Champaign, Illinois) and had below average grain yield in 5 of 10 years between 2005 and 2014 that coincided with water deficiencies (see Table 36 in Appendix). They contributed approximately 52% of the nitrogen to the Gulf of Mexico in 2014 (USEPA, 2014). .

The UCSD NE-WTP currently produces approximately 400,000 L centrate/d (unpublished data, 2012. Urbana, IL: Urbana-Champaign Sanitary District). Their current solution for centrate management is redirection of this high strength wastewater to its head works, whereby the high concentration of NH_3 significantly reduces nitrogen treatment efficiency (Wett, Rostek et al. 1998).

The first objective of the study was to evaluate corn grain yield and plant nitrogen uptake with AD centrate or urea. The second objective was to assess nitrogen and water movement away from an SI pipe in unsaturated soil conditions.

Following this chapter, a literature review in Chapter 2 is presented that will briefly review how nitrogen interacts with plants and soils to become available to plants. Then, a discussion of how centrate is a problem to be addressed in WTP nitrogen treatment will be provided, followed by how the problem of nitrogen is a mutual one for WTPs and farmers. A short discussion of water management in agriculture will conclude Chapter 2. Chapter 3 proposes a broader model that maximizes the benefits of partnering agricultural nitrogen and water management with AD-operating WTPs in a year-round treatment and utilization strategy. Chapter 4 lists and describes the project's materials and methods. Chapter 5 presents the experimental results and discussion for the 2013 and 2014 growing seasons. Chapter 6 summarizes the most important conclusions and presents recommendations for future work.

CHAPTER 2: LITERATURE

Nitrogen: the Resource

Role in the Plant & Uptake

The amino acids and nucleic acids that constitute proteins and make all life possible require nitrogen (Liu, Yang, & Yang, 2012). Unlike carbon, hydrogen, and oxygen that are abundant in the plant, nitrogen is not directly available from air or water (Equation 1).

$$6\ CO_2 + 6\ H_2O \overset{\text{Light}}{\rightarrow} C_6H_{12}O_6 + 6\ O_2$$

Equation 1. The general photosynthesis reaction

For corn, on which 33% of Illinois' total *land area* was planted in 2014 (USDA, 2015) nitrogen must be assimilated through the roots as inorganic nitrogen (NH_4^+, NO_x) present in the soil. For a 14,400 kg/ha grain yield, as much as 287 kg N/ha may be assimilated (Table 1).

Table 1. Nutrient uptake for corn (adapted from Bender, Haegele et al. 2013)

Nutrient	**Uptake (kg/ha)**
N	287
P_2O_5	113
K_2O	202
S	25
Zn (g)	490
B (g)	84
Each value is a mean of six hybrids at two locations (mean = 14400 kg/ha).	

While plants will utilize all inorganic forms of nitrogen to build its biomass, and even low molecular weight dissolved organic nitrogen (Jones, Shannon et al. 2004), NH_4^+ is preferred, and there is even evidence that a particular ratio of $NH_4^+ : NO_3^-$ is more beneficial. (Below and

Gentry, 1992; Below and Smiciklas, 1992). While the specific ratio (50:50) is unattainable at a precise level in a setting as dynamic and uncontrolled as an outdoor field; the most widely-applied fertilizers, anhydrous ammonia (NH_3) and granular urea $CO(NH_2)_2$ (Pioneer, 2015), do not directly supply both forms of nitrogen to plants.

Nitrogen Availability

Since nitrogen plays such a vital role in plant structure and metabolism, the addition of it to soil in the form of animal manure, has long been utilized for fertilization; but, in manure, 20 to 80% of the nitrogen is organic and not immediately available to plants (Beegle, Kelling, et al. 2008).

A diagram of the nitrogen cycle is shown below to illustrate the key processes affecting N availability to both plants and their inorganic nitrogen competitors, microbes—immobilization (heterotrophic microbes), mineralization (heterotrophic microbes), and assimilation (plants).

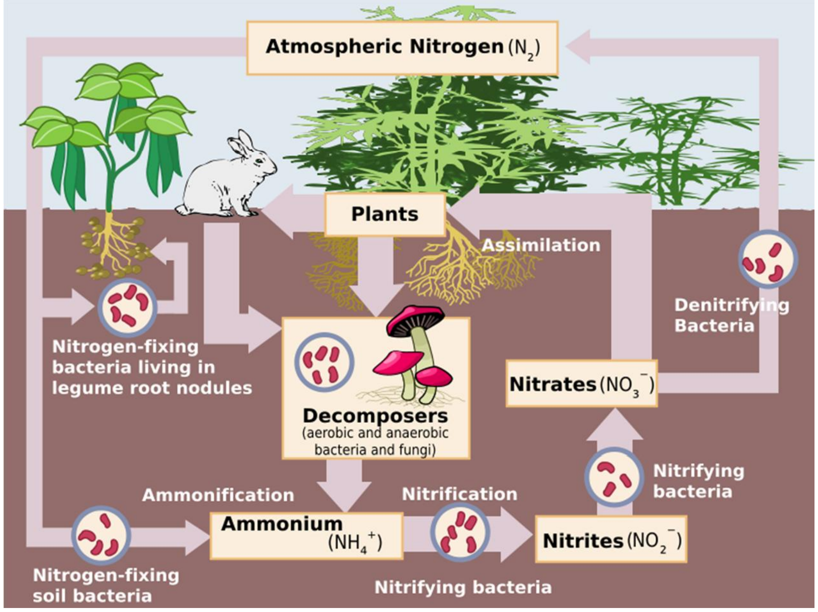


Figure 1. The nitrogen cycle (EPA, 2013)

Avoiding the loss of nitrogen in the interval between application and uptake is a challenge, given the highly dynamic conditions effecting its loss in the field illustrated in Figure 1. Applying excess nitrogen, in advance, to compensate for this loss is only a short term solution that costs the farmer more money and compromises environmental and soil quality. As much as 60 mg NO_3^--N/L was reported for the spring drainage tile discharge in a study by Colbourn (1985). This is approximately twice the concentration of influent municipal wastewater!

Further discussion on how inorganic nitrogen can affect the environment and soil quality will be discussed. First, it is important to understand what factors affect nitrogen management decisions.

Plant Content

Traditionally, a large number of nitrogen applications were based upon the imperial formula, applied lbs. N/A = yield goal (bu/A) * 1.2. This was first recorded by Swanson, Taylor et al. (1973).

Since that time, and the increase in awareness of environmental concerns associated with over applying nitrogen, university extension services recommend to farmers a more conservative approach that accounts for more variables affecting nitrogen availability as well as the tradeoff between the cost of nitrogen and value of grain (Table 2). On the following page is such an example.

Table 2. Rate of return nitrogen recommendations

Price	**Corn Following Soybean**		**Corn Following Corn**	
Ratio[1]	Rate[2]	Range[3]	Rate[2]	Range[3]
\$/kg:\$/kg	- - - - - - - - - - - - - - - kg N/hectare - - - - - - - - - - - - - - -			
0.11	163	146 to 183	230	210 to 255
0.22	139	124 to 158	203	185 to 220
0.33	123	109 to 138	177	163 to 195
0.44	109	96 to 121	163	146 to 175

Environmental Conditions

The primary sink for inorganic N other than the plant is through immobilization in other microbes. The rate at which this takes place is contingent upon temperature, water availability, and oxygen (Wang, Chalk, et al. 2001; Hey, Xu, et al. 2014). The effects that these factors can have on the results of nitrogen application timing are significant. Williams et al. (2012) showed that the difference between early fall and winter manure treatments accounted for an average of 14% less overwinter inorganic nitrogen loss, either as runoff or as leachate. Rolison (2012) showed 157 to 441% greater nitrification rates in the A (upper) soil horizon compared to the B (lower) soil horizon.

Synthetic Production

Important to the discussion of nitrogen in agriculture is the effect that the production of synthetic nitrogen has had on world population as well as requirements of the process.

With the utilization of the Haber-Bosch process for NH_3-based fertilizer synthesis following WWII (Figure 2), inorganic nitrogen became directly and plentifully available to farmers for plant fertilization. In this process, the virtually inexhaustible supply of atmospheric N_2 became accessible as shown in Equation 2.

$$N_2 + 3\ H_2 \rightarrow NH_3 \qquad \Delta H = -92.3\ \text{kJ/mol}$$

Equation 2. Synthetic generation of NH_3

In the late 1990s, most NH_3-production plants required approximately 33 GJ/ton NH_3-N and over 100 million times this quantity is produced annually—100 Mt/yr (Smil, 2001). Despite general concerns about global energy supplies (Nejat, Jomehzadeh, et al. 2014; Szulecki and Westphal, 2014; Winter, Faße, et al., 2014) the application, and consequential demand, for fertilizer N appears to only be increasing—stimulating with it world population growth (Figure 2).

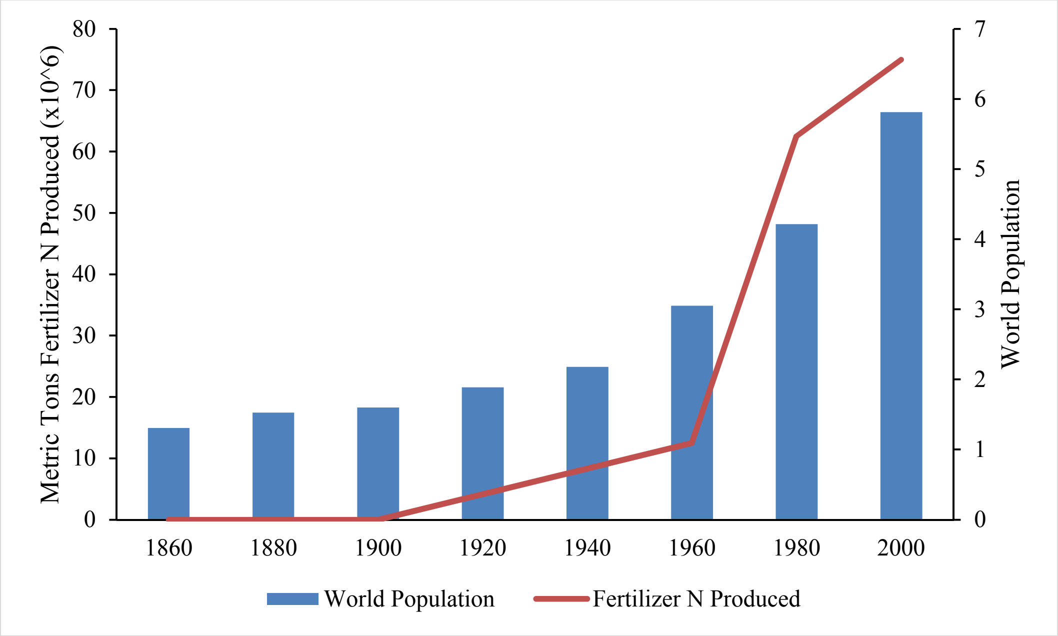


Figure 2. Relationship between increasing fertilizer N production and population growth (Redrawn from Jenkinson, 2001)

Nitrogen: the Problem

Early in modern wastewater treatment, WTPs typically focused on removing only solids through various means of oxidation and settling (primary and secondary treatment). Nitrogen was only removed incidentally through these processes as organic nitrogen or adsorbed inorganic nitrogen. When the consequences of nitrogen contamination in waterways became more apparent—NH_3 toxicity by aquatic organisms (Erickson, 1985), coastal hypoxia (Conley, Carstensen et al. 2011), and NO_3^- groundwater pollution (Sawyer, 2015)—WTPs experienced the added responsibility of maintaining certain nitrogen levels as well, beginning with NH_3-N and others having treatment standards for total N as well (US EPA, 1972). The production of centrate has enhanced the costs associated with this treatment (Wett, Rostek et al. 1998).

This section will explain how centrate is generated and what factors affect the quantity produced, the costs of conventional nitrogen treatment, and current solutions to more efficiently treat the nitrogen in centrate.

Centrate Production

The unique nature of centrate is such that it is actually produced as part of the WTP processes. This is done through dewatering of solids having undergone anaerobic digestion—a strategy to reduce the volume of solids that the WTP needs to manage. When this centrate is redirected to the head works, the total influent NH_3 concentration can increase by as much as 15 to 20%, despite centrate contributing only 1% of the influent volume (Bartrolí, Garcia-Belinchon et al. 2013, Baumgartner, Glenn et al. 2005; Holloway, Childress et al. 2007).

The apparent irony associated with producing wastewater within a WTP is ignored by the benefit of creating value added co-products associated with the process (Figure 3).

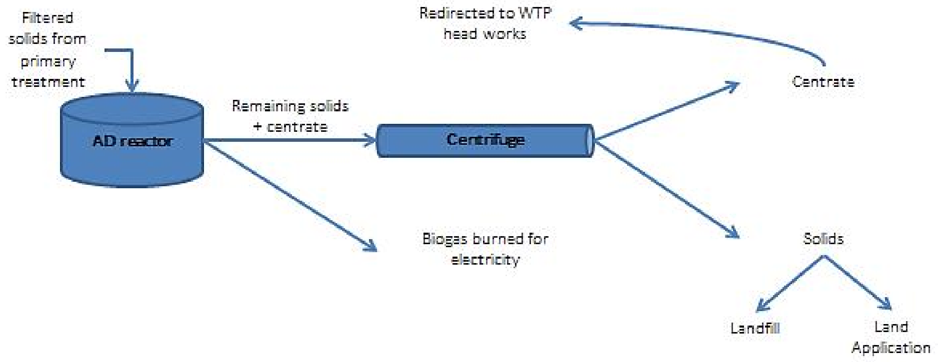


Figure 3. The anaerobic digestion process with products: biogas, solids, and centrate

Enhanced Centrate Production

The volume of centrate produced relative to the total influent is small. This is due to the relatively long retention times for complete digestion of volatile solids and reduced rates of digestion as SRT (solid retention time) increases (Cacho, 2005). Work though, by Martin-Ryales (2012), has indicated the potential of reducing this time through bioaugmentation and alkaline pretreatment of the solids to go through AD. This would increase the production of methane which can be combusted and used for electricity at the WTP.

Centrate production, then, would increase. Rather than the generation of more centrate being a small negative associated with more methane production, the additional centrate could be an additional positive associated with Martin-Ryales' proposed system.

Treatment Costs

Cost for treatment of nitrogen varies—based upon concentration, capital investment in equipment, technologies selected, and the processes utilized in nitrogen treatment (nitrification and/or denitrification). Work done by Hey, Kostel et al. (2005), estimated an average cost for annual total N (TN) removal at seven WTPs in the suburban Chicago area, based upon capital investment and energy use, to be $8,130/ton TN. They estimated similar values for seven similarly-sized WTPs in Long Island Sound ($6,870/ton TN). This can be performed in contained structures—biological and chemically—or through land application (Tchobanoglous, Burton, et al. 2003).

Among the nitrogen treatment processes, land application is unique with respect to its long history, its large land area requirement, and its value-added byproducts (irrigated crops). In the mid- to late-19th century, most of the 143 WTPs in the United States in the mid- to late-19th century practiced some form of land application (Rafter and Bayer, 1894). Rafter's comprehensive review of US wastewater disposal practices concluded that "properly managed" sewage farms were not threatening to health. Its ultimate decline from this apparent ubiquity and studied effectiveness is cited as (Crites, 2001)

- Pressures for alternative land use
- Overloading application sites due to incomplete technical understanding of the process
- The ubiquitous acceptance of Pasteur's germ theory for disease transmission
- The introduction of chlorine for purification
- Technical knowledge for space-saving trickling filters and activated sludge became widely available by the 1920s

In 1972, though, a path to more prevalent integration of land application was inspired by the Clean Water Act's goal to "eliminate the discharge of pollutants into the navigable waters, waters of the contiguous zone, and the oceans". Today, WTP designers and engineers routinely consider land application as a strategy (Crites, 2001); despite this, significant obstacles are still in place to its more widespread applicability

- pressure for alternative land uses
- negative public perception (odor, appearance)
- low nitrogen concentration
- limited allowable application days due to wind and precipitation
- investment in expensive overhead structures

For these reasons, careful planning of a model of land application that maximizes production on less land area, is not visible or olfactible to passers-by, and can be utilized in a wide variety of weather and topographical conditions.

Current Strategies for Centrate-Nitrogen Treatment

A summary of these strategies is shown in Table 3 below.

Table 3. Alternative strategies for centrate treatment

Centrate Treatment Process	Description
Independent nitrification (Bartroli Garcia-Belinchon et al. 2013; Husband, Phillips et al. 2010)	Centrate NH_3-N is nitrified apart from primary treatment stream
Aerobic membrane bioreactors (Chandrasekeran, Urgan-Demirtas et al. 2007)	Utilization of high nitrifier population in biomass with membrane to achieve complete nitrification under longer hydraulic retention times
Carbon-added denitrification (Chen, Lee et al. 2013)	Utilization of carbon-based additives to complete the N-removal process; can utilize biomass residues from industrial processing
Value-added struvite precipitation (Doyle and Parsons, 2002; Garcia-Belinchon, Rieck et al. 2013; Karabegovic, Uldal et al. 2013; Lew, Phalah et al. 2011; Mavinic, Koch. et al. 2007)	Controlling pH and adding magnesium to facilitate the precipitation of the value-added co-product: struvite
Electrochemical denitrification (Xie, Li et al. 2006)	Utilized in locations with saline wastewater from the use of sea water in toilets

Nitrogen: the Mutual Problem

Both agriculture and WTPs play a key role in effecting nitrogen's ultimate presence in air and water environments. This section will examine and describe regional and global consequences of surplus nitrogen influx.

Gulf of Mexico Hypoxia

The Upper Mississippi River watershed contributes between 1,120 (Turner and Rabalais, 2004) and 1,229 (Goolsby, Battaglin et al. 1999) kg total N $\cdot$ km^{-2} $\cdot$ yr^{-1}. In 2014, the Gulf of Mexico hypoxic zone was approximately 13,080 km^2, caused by decaying, nitrate-fed algal blooms (US EPA, 2014). It is in the eventual die off and decomposition of these algal blooms which consumes the dissolved oxygen in the water that induces hypoxia (dissolved $O_2 < 2.0$

mg/L) and compromises the viability of aerobic organisms. Figure 4 illustrates the extent of the problem at the global level. Red shading on land masses indicates higher population densities. Blue shading on oceans indicates higher levels of particulate organic carbon. Shaded red circles along coasts indicate the location and relative size of hypoxic zones. Black dots along coasts indicate hypoxic zones of unknown size.

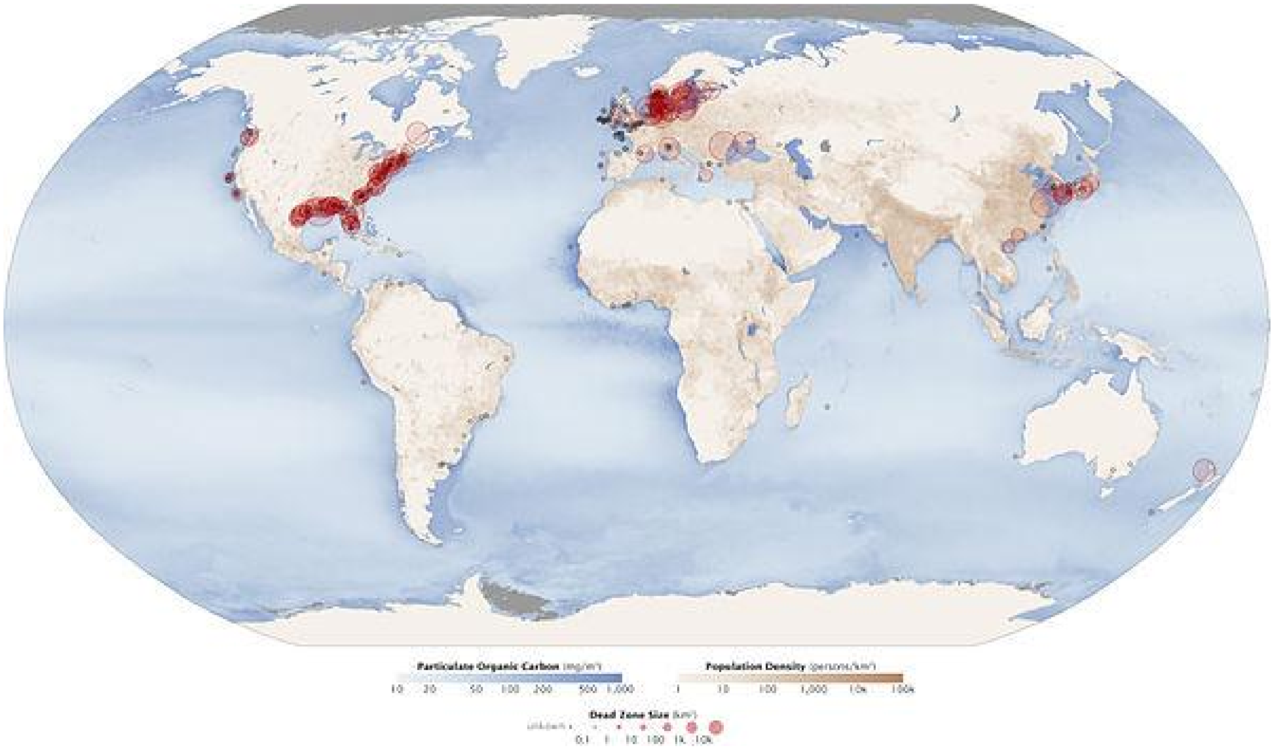


Figure 4. Global hypoxic zones (NASA Earth Observatory, 2010)

Along coasts, this problem is particularly detrimental to crustaceans and other organisms that walk along the bottom who are unable to sufficiently move to a new, more aerobic environment. Fish are less affected in that they can more easily and quickly move away. Coastal fisheries must then expend more energy and money to move further from the hypoxic zones along the coast. Figure 5 shows the relative contributions of crop-agriculture and urban-area sources.

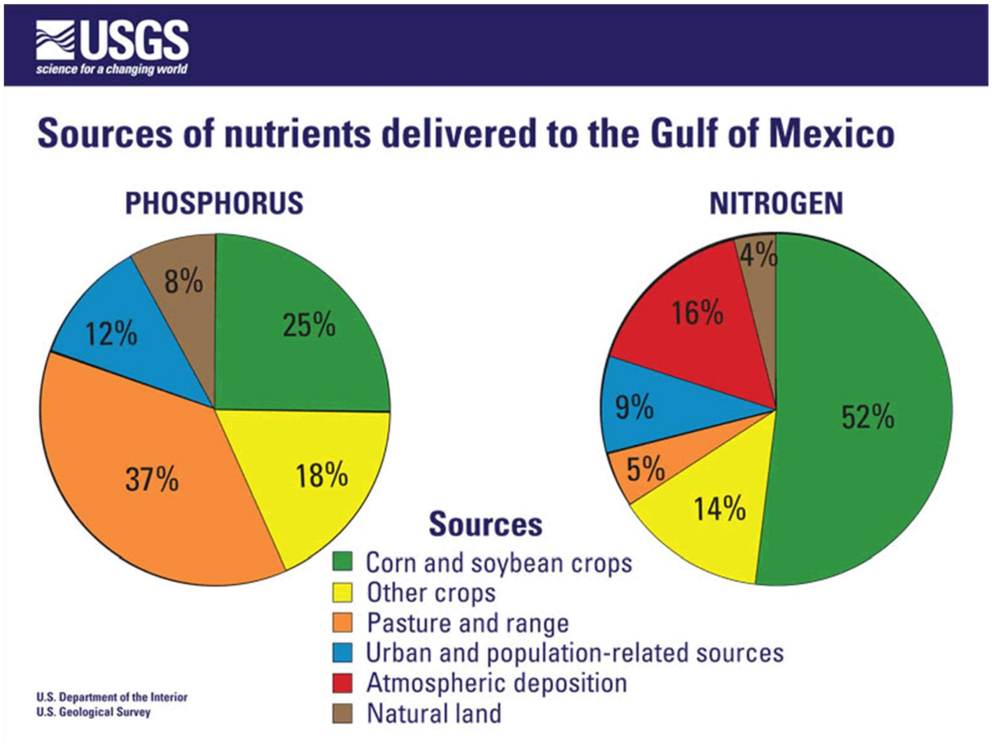


Figure 5. The relative contributions of crop-agriculture and urban-related sources (USGS, 2014)

Greenhouse gas emissions

The majority of nitrogen in air is benign and highly inert as N_2 ($\Delta H=946$ kJ)—only directly accessible to the legumes such as soybeans with symbiotic associations; however, nitrogen also exists in the air in other significant forms—nitrous oxide (N_2O) (North Carolina State University, 2013), a greenhouse gas (GHG), and NH_3. The presence of each N species in the environment is influenced by agricultural and WTP nitrogen management (Figure 6).

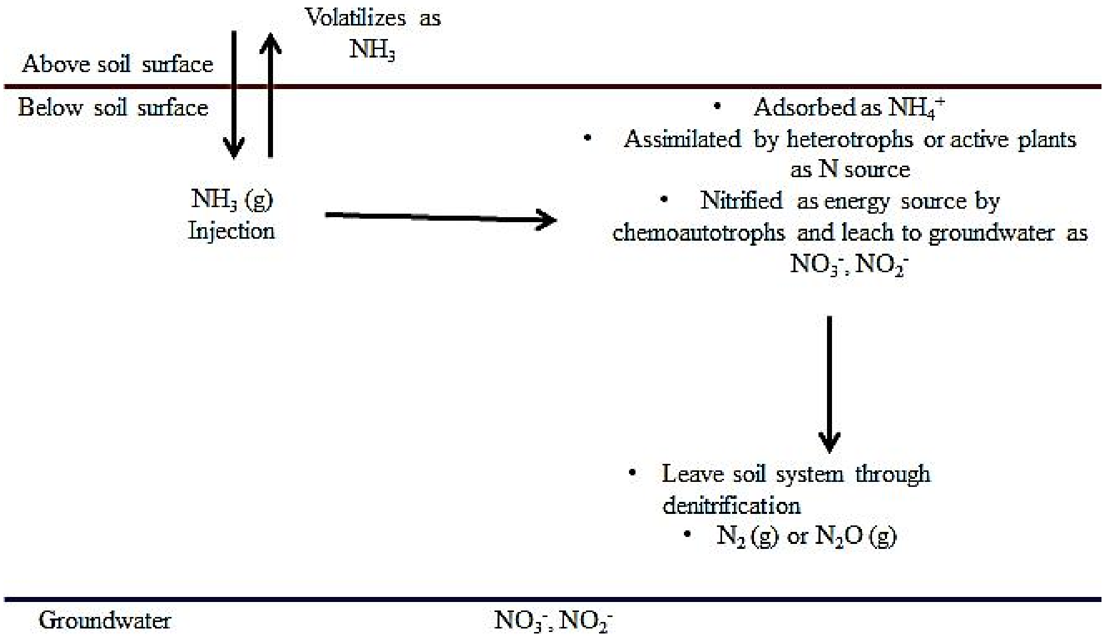


Figure 6. The nitrogen flux pathways following anhydrous NH_3 injection

N_2O is an intermediate in the denitrification of NO_3^- to N_2 and contributes over 300 times the radiative forcing per unit mass of CO_2 (Shine, Fouqart et al. 1995). Agriculture contributes approximately 67% of these total national N_2O emissions (USEPA, 2009). These losses, to water and air, come at a cost, not only to the farmer through his or her reduced nitrogen use efficiency (NUE), but to the global buildup of GHGs.

Groundwater pollution

Because most soils have a relatively small number of exchange sites to which anions can adsorb (Sanchez, 1976; Buckman and Brady, 1967), nitrate is frequently present in groundwater due to leaching. In 2005, it was estimated that 6% of Illinois' land area has groundwater greater than 5 mg NO_3^-- N/L (USEPA, 2015). A concentration of 10 mg/L NO_3^--N is the maximum allowable concentration for permitted discharges (USEPA, 2015). Rural residents with underground wells to access drinking water may inadvertently consume leached nitrates from nearby fields.

When nitrate is consumed, a form of hypoxia can result known as methemoglobinemia (WHO, 2011). Additionally, nitrate-based substances can react with certain compounds in the stomach—forming "N-nitroso" compounds which are carcinogenic in animals (USEPA, 2014).

Soil Organic Carbon Loss

Recall that competition for inorganic nitrogen is not just among plants, but microbes as well. Immobilization of inorganic nitrogen by microbes may account for 60 kg N/ha in a year (DRAINMOD, 2015). Upon the sudden flux of inorganic nitrogen in fertilizers, soil microbes increase consumption of soil carbon for either their energy source (chemoheterotrophs) or substrate structure (chemoautotrophs). In either circumstance, the increased metabolic activity of the microbes increases the oxidation of soil carbon into the atmosphere as CO_2.

A meta-analysis of long term soil studies (Mulvaney, Khan, and Ellsworth, 2009) demonstrates this pattern. The analysis surveyed 120 long term soil experiments from around the world, ranging in length from 4 to 107 years.

Further, this process can actually be enhanced by drainage in former wetlands or marsh prairies such as in East Central Illinois. This increased quantity of aerobic zones in the soil increases the number of environments favorable for aerobic soil heterotrophs and chemoautotrophs, which results in increased soil oxidation in previously anaerobic (wet) sites (Hadi, Haridi et al. 2001; Inubushi, Otake et al. 2005).

Carbon Footprint

As mentioned earlier, 33 GJ is required to produce 1 ton of NH_3-N. To further process the NH_3-N, used as a substrate to produce granular urea, at least 35% more energy is needed (UNIDO, 1998). This does not even take into account costs for

- Fertilizer transportation from the synthesizing factory
- Production and maintenance of nitrogen application equipment (anhydrous ammonia tanks, application bars and knives, nitrification inhibitors, etc.)
- Costs for direct field application (fuel, tractor and equipment maintenance)

In fact, for knifing in NH_3-N to a 404 ha field, the same quantity of CO_2 would be released as that by a light weight car travelling 1.5 times around the Earth's equator (Helsel and Oguntunde, 1985).

Water

This section will briefly examine the history of drainage and its benefits, consequences associated with water deficiency in agriculture, and current and anticipated changes in climate patterns that would enhance these deficiencies. Finally, this section will identify and describe a new strategy that can *manage* the water table height and address the obstacles associated with limited applicability of land application of wastewater that were identified earlier.

Free Drainage Tile Systems

In east-central Illinois, the primary means for water management has been largely a factor of *reducing* its presence through the installation of free drainage tile systems by draining wetlands and lowering shallow water tables to increase trafficability and aerobic zones in the soil. This is evident from the ubiquitous presence of drainage tiles on a drive through east-central

Illinois—drainage outlets discharging to ditches and the presence of orange, upright surface outlets across low-lying areas in fields.

The presence of drainage can increase grain yield by allowing earlier trafficability and planting and increasing soil air content. Table 4 below illustrates the benefits of drainage on corn grain yield for a silty-clay soil in Ohio based upon average production over 13 years.

Table 4. Differences in corn yield (kg/ha) with respect to drainage types (recreated from Schwab, et al. 1985)

No Drainage	Surface Drainage	Tile Drainage	Surface and Tile
3200	4900	6150	6410

Precisely how much land is drained in the US is not known because no reporting of installed drainage is required by any organization; however, satellite and aerial imagery has been used to provide some estimates. According to Thayn et al. (2011), over half of the US wetlands were drained by 1987 and as much as 95% in some states. The net benefit of drainage though is compromised by the decrease in plant available water during the dry summer months.

The data on the following page (Table 5) demonstrate the enhanced corn grain yield in south central Illinois on a clay soil when water is both removed early in the growing season through drainage and then added during the dry summer through sprinkler irrigation.

Table 5. The enhanced effects of both drainage and sprinkler irrigation on corn production (Walker, et al. 1982)

Drainage system	Irrigation Treatment (kg/ha)	
	None	**Sprinkler**
None	4200	950
Surface and tile	5000	8270

Water Deficiencies & Climate Change

Weather patterns are expected to become only more extreme in their severity due to climate change (O'Gorman and Schneider, 2009)—making the importance of both timely drainage and irrigation more important.

Globally, the Palmer Drought Stress Index represents the increasing frequency of droughts since 1900 (Figure 7).

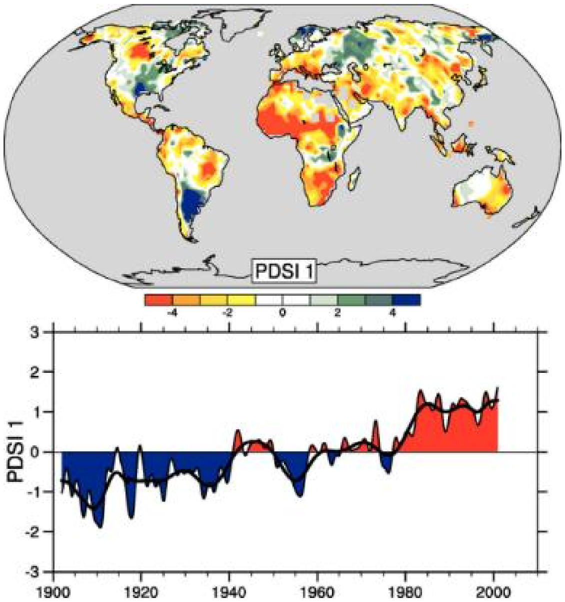


Figure 7. The Palmer Drought Stress Index measures the cumulative deviation for precipitation with respect to average surface area precipitation values for the previous 100 years (IPCC, 2007)

Farmers have responded to this present reality and future concern—particularly in the Corn Belt. Figure 8 shows the general upward trend for agricultural irrigation between 1982 and 2007 for various regions in the US.

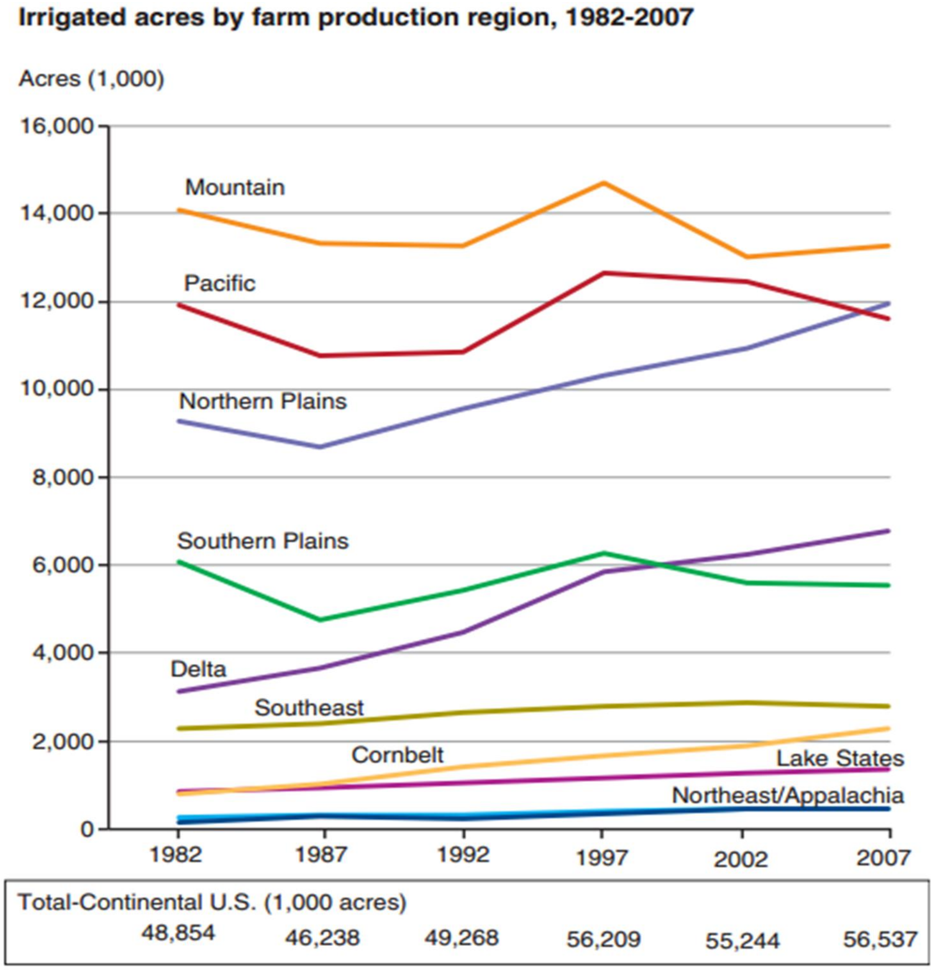


Figure 8. Irrigation trends in the United States from 1982 to 2007. (Schwaible and Aillery, 2012)

Installation of overhead irrigation can cost $1,600 to $4,200/ha. Return of investment for overhead irrigation typically runs 5 to 7 years (unpublished data, 2012. East Prairie, MO: MRM Ag Services). Additionally, operation requires low slopes, installation of a well and either a diesel engine to power it or extension of the electrical grid. A system that pays for itself faster and can be more broadly applied to varying field topographies and circumstances is needed.

Subirrigation Controlled Drainage (SI-CD)

Installation of a new SI-CD system can cost $7,000/ha; but, fuel costs for pumping can be as low as $20/ha/season (unpublished data, 2003. Agrem, LLC). The application of a SI-CD is a strategy that can strategically complement centrate use for corn production with its general invisibility on the surface and limited exposure to the air for any odor escape from the centrate. These SI systems can be integrated to an existing drainage system or installed new. Figure 9 illustrates the operation of a control gate mechanism to slow field water drainage.

Figure 9 & 10. (Left) The top view of a control gate (managing two different water table heights in the field (Agrem, 2009). Relative control gate size (right)

The table below shows the beneficial effects of using SI to remove water in the spring and fall and store and add water to the field during the growing season.

Table 6. The beneficial effect of subirrigation for corn and soybean yield as demonstrated by these studies.

	Location	Drainage spacing (m)	Corn (kg/ha) (Numbers in parentheses indicate the number of years measured that differs from the study's duration)		Soybeans (kg/ha)	
			Free Drainage	SI	FD	SI
Allred, Brown et al. 2003	Defiance County, MO (1997-2001)		6450 (4)	7247	969 (3)	1896 (4)
	Fulton County (1996-2001)		8776	12047	3621	4416
	Van Wert County (1997-2001)		10176	10858	3086	3323
Nelson, Smoot et al. 2007	Northeast MO (2003 – 2006)	6.1			3870 +/- 827	4070 +/- 726
		12.2			3820 +/- 1000	3930 +/- 720
Cooper, Fausey et al. 1999	Wooster, OH (1990-1992)	6.1	9790	12700		
	Hoytville, OH (1992-1994)		10500	11700		

CHAPTER 3: PROPOSED SYSTEM DESIGN & PROJECT OBJECTIVES

The main purpose of this study was to demonstrate centrate as an effective nitrogen alternative and supplemental water source for corn grain producers that could be applied through an SI system.

In this section, a model will be proposed that allows for year round utilization and treatment of centrate along with a final review of the project objective before the Material & Methods in Chapter 4.

Proposed System Design

In this proposed model for year round centrate treatment and reuse there are four parts each year (Table 7).

Table 7. Seasonal schedule of proposed system design

Scheduled	SI Application Site	Defining Factors
May 1 to July 31	Reuse for Agriculture-Growing Season	• Incremental nitrogen and water applications to maximize nitrogen uptake during highest rates of plant assimilation • Excess N reduces need for initial investment (time, planning, cost) and enhances corn growth as a value-added by product
Aug. 1 to Oct. 31	Marsh Grassland	• Increased trafficability for harvest • Allows for enhanced grassland activity towards end of growing season
Nov. 1 to Feb. 28	Reuse for Agriculture-Nitrogen Buildup	• Displaces and reduces losses associated with fall anhydrous ammonia application • Increases cation exchange site saturation with NH_4^+
Mar. 1 to Apr. 30	Marsh Grassland	• Allows for increased corn field trafficability • Enhance early season growth in grassland

May 1 to July 31 Reuse for Agriculture

A significant obstacle associated with implementing systems for land application of wastewater has been the relatively large land area required for its sustainable operation. A benefit of centrate wastewater is the high concentration of NH_3-N compared to influent wastewater. Table 8 compares the volume of water required to apply 224 kg/ha NH_3-N to corn through influent and centrate, respectively. Ammonia concentrations are based upon unpublished UCSD data (2012).

Table 8. Relative amount of wastewater required for 1 ha of corn to receive 224 NH_3-N kg/ha

Wastewater	Liters/d (Millions)	NH_3-N (mg/L)	cm wastewater	Precipitation (cm)[1]
Primary effluent	41.22	22.9	98.6	45.5
Centrate	0.19	937	2.41	
[1]Urbana weather station: Average precipitation May 1 to Aug. 31, 1981-2010 (MRCC, 2015)				

Land applying influent to corn, at a rate that would equal 224 kg NH_3-N/ha, would require infrastructure to transmit approximately 98.6 cm of water. With such a large volume, equipment would need to be purchased and installed in order to monitor soil moisture so as to not oversaturate corn roots. The 98.6 cm of water added as influent, in addition to 45.5 cm of average precipitation during the growing season, would be distributing 219% of the corn's water needs during the growing season (Kranz, Irmak et al. 2008).

In contrast, applying centrate at the same nitrogen rate to corn would require only 2.41 cm of water. If more water was desired during certain drought conditions, the centrate could be diluted with final effluent at the WTP using the same irrigation infrastructure.

Aug. 1 to Oct. 31 & Mar. 1 to Apr. 30 Marsh Grassland

A marsh grassland in the system serves three purposes:

- Reducing the need for centrate redirection to head works on non-application days IEPA-regulated land application of wastewater (See Table 37 in the Appendix for more information)

- Can be harvested in the spring and fall as a biofuel source to enhance nutrient uptake
- Can be developed along the fringes of the corn field application sites to mitigate groundwater contamination risk
- Enhancing positive public perception of the system

Nov. 1 to Feb. 28 Reuse for Agriculture-Nitrogen Buildup

As a time management strategy, farmers apply nitrogen as anhydrous ammonia in the fall once soil temperatures have dropped to below 10°C. Recall that nitrate concentrations as high as 60 mg NO_3^--N/L have been recorded in drainage tile discharge. Such high losses occur because

- Volatilization
  - pH and soil moisture determine the quantity of ammonia that becomes sorbed as NH_4^+ or lost as NH_3 gas
- Nitrification and Leaching
  - Anhydrous ammonia is typically not applied until soil temperatures are low in order to minimize exposure of NH_3 to nitrifying microbes which are more active in warmer temperatures
  - Microbes will convert NH_3 to NO_3^- which is not as tightly bound by the anion exchange sites
  - This process is enhanced by the presence of oxygen—made more readily available by the application knives cutting open the soil surface and the relatively shallow application depth (15 cm)

In the system proposed in this study, during the non-growing season, nitrogen could be applied and stored in a similar way, but fewer losses would occur because more moisture would be present (Bender, unpublished data, 2014. Urbana, IL: University of Illinois) and less oxygen would be available at the depths of SI tiles (60 cm) compared to the depths of application for anhydrous ammonia tines (15 cm).

Research Objectives

The scope for this work focused on evaluating factors relevant to utilizing AD centrate as a nitrogen and water source for corn.

The following were the research objectives:

1. To evaluate corn grain yield and plant nitrogen uptake with AD centrate or urea through SI
2. To assess nitrogen and water movement away from an SI pipe in unsaturated soil conditions

Objective 1

As stated earlier, considering strategies that can maintain or enhance grain yield to feed a growing world population through sustainable methods is essential. In order to demonstrate centrate with SI for corn growth, grain yield was measured and compared for treatments receiving centrate or urea through SI and urea that was topically applied, with no supplemental irrigation, in the summers of 2013 and 2014.

Objective 2

Nitrogen is highly dynamic in the soil—sought after as an essential micronutrient by all life and changing forms through biological and chemical processes. By understanding these processes and measuring them, further work can be done to optimize its availability in the soil through the use of this system.

CHAPTER 4: MATERIALS & METHODS

Materials

Evaluation of Centrate for Producing Grain Yield & Enhancing Nitrogen Uptake

Agricultural Engineering Research Farm at the University of Illinois Urbana-Champaign

Both fields were located within the University of Illinois Agricultural & Biological Engineering Research Farms, located at 44°04’N, 88°12’W. Two fields were used and are physically and chemically characterized in Table 9 (Champaign County Soil Survey, 2012). Topography with respect to the surrounding area is shown in Figure 11 (Google Earth, 2014). Detailed topographical maps of both fields are shown in Figures 12 & 13 (Surfer Pro, 2014).

Table 9. Physical and chemical soil properties

	SI Field (2013-2014)		**Non-SI Field (2014)**	
Soil series	**Brenton silt loam**		**Drummer silty clay loam**	
Soil Parameter (all calculated as “weighted averages)	**All Layers (0 to 180 cm)**	**0 to 75 cm**	**All Layers (0 to 150 cm)**	**0 to 75 cm**
CEC-7 (weighted average)	16.7	20.6	23.6	27.4
pH	6.7	6.6	7.0	6.8
% OM	1.18	2.44	1.93	3.30
% sand	25.6	5.1	18.7	7.9
% silt	50.3	68.1	52.8	60.8
% clay	24.1	26.8	28.5	31.3
BD (1/3 bars) (g/cm^3)	1.47	1.39	1.38	1.32
K_{sat} (cm/s)	4.59	3.30	3.41	3.23
Depth to a restrictive layer	>200 cm		>200 cm	

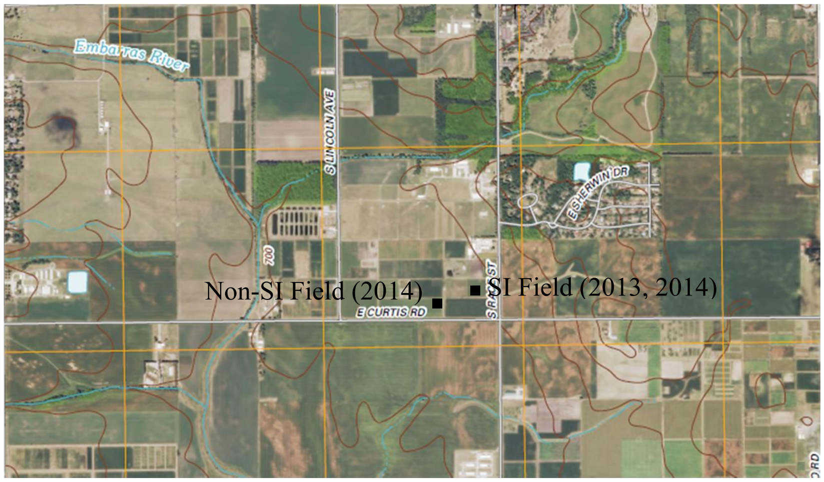


Figure 11. Field and surrounding area topography (USGS, 2012).

The "700" contour line corresponds to 213 m. Each line to the right of "700" indicates an increase in elevation of approximately 3.0 m.

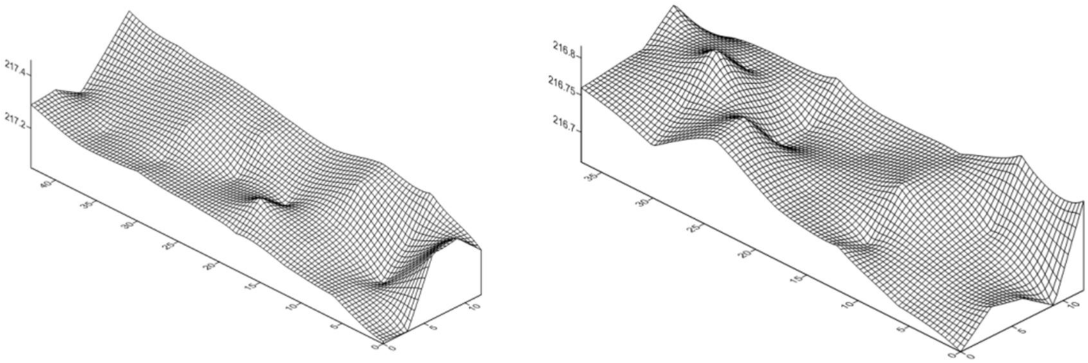


Figure 12 & 13. SI field topography (meters, left) Non-SI field topography (Surfer Pro, 2014).

Soil Sampling & Analysis

Soil cores were removed using a manual jack soil probe (manufactured by Clements Assoicates, Inc.) for sampling to depths of 0 to 30 and 30 to 60 cm. Soil samples were immediately dried for at least 24 hours at 75°C, crushed to 2 mm diameter or less, then analyzed for inorganic N using the Accelerated Diffusion of Inorganic Nitrogen (Khan, Mulvaney, and Mulvaney 1997).

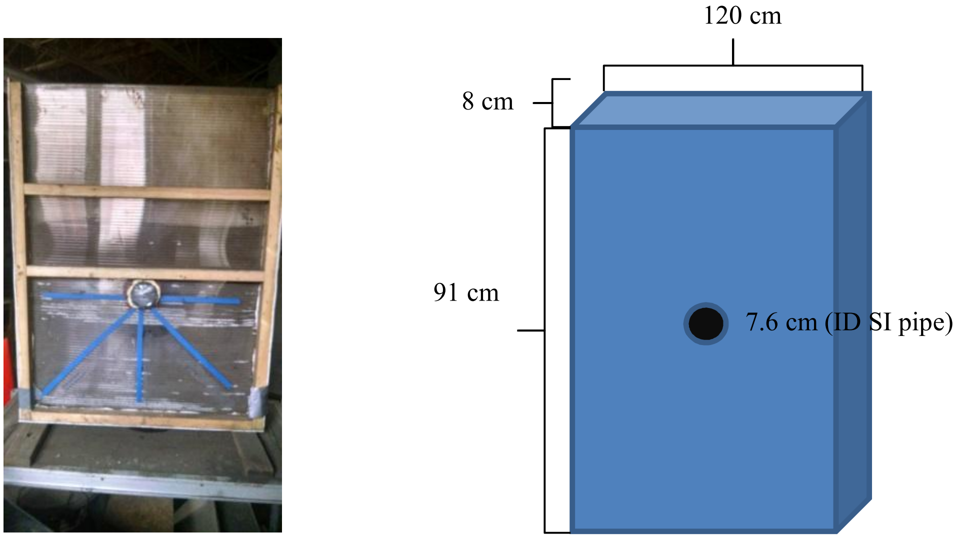
Centrate Analysis

Centrate was used from the UCSD NE-WTP and transported in 760 L increments by pick-up truck. Total N and NH_3-N in the centrate samples were analyzed using the Persulfate Digestion method (5 to 40 mg/L) and the High Range Ammonia Nitrogen AmVer^{TM} Salicylate Test 'N Tube Method (0.4 to 50 mg/L NH_3-N), respectively. All samples were frozen between one and two months between collection and analysis. Estimates of the centrate NH_3-N and Total N used in the project are shown in the Appendix.

Assessing Nitrogen & Water Movement

Soil Profile Box

The soil profile box was used for measuring the physical movement of water away from an SI pipe in unsaturated soil conditions. This measurement would allow the study to accurately apply the chemical and biological soil principles discussed in the following sections.



Figures 14 & 15. The soil profile box and dimensions

The soil profile box (pictured, above) was constructed according to the dimensions shown in the figure and listed in Table 10 below. Note that the dimensions of certain products are imperial units. An x and y axis grid was adhered to the transparent face of the box (shown) with the center of the pipe at the origin (0,0) in order to measure water movement away from the pipe.

Table 10. Soil profile box dimensions and materials

Quantity	Dimensions	Description
4	1 in. x 1 in. x 120 cm	Wood, form 4 corner, height-wise supports
4	1 in. x 1 in. x 91 cm	Wood, form 2 front retaining pieces (visible in image) and 2 back retaining pieces
2	2 in. x 4 in. x 60 cm	Floor supports
1	¼ in. x 91 cm x 120 cm	Transparent, polyethylene sheet, form front face
1	¼ in. x 91 cm x 120 cm	Opaque, polyethylene sheet, form back face
2	¼ in. x 8 cm x 120 cm	Opaque, polyethylene sheets, form side retaining walls
1	¼ in. x 8 cm x 91 cm	Forms bottom
100	$^{3}/_{8}$ in. metal sheet screws	Secure materials
100	3 in. multi-purpose screws	Secure materials
100	2 in. multi-purpose screws	Secure materials
1 tube		Expanding silicone
1 tube		Non-expanding silicone

Methods

Evaluation of Centrate for Producing Grain Yield & Enhancing Nitrogen Uptake

2013 Field Management (Full Fertilizer Management Details Can Be Found in Table 40 in the Appendix)

A 43 x 15 m field corner was selected on the Agricultural & Biological Engineering Farm in May 2013. Five SI pipes (Table 11) were installed in the center of each planned SI treatment plot in June 2013 using a Vermeer 3-point hitch tractor trencher with 1.2 m boom to an approximate depth of 60 cm on the SI treatment plots (Table 13).

Table 11. SI pipe specifications

Parameter	Description
Inner diameter	7.6 cm
Outer diameter	8.9 cm
Evacuation points	0.15x1.3 cm slits (located every 90º around the pipe)
Material	Corrugated polyvinyl chloride

Table 12. 2013 plot design

Treatment	No. of Plots | No. of Samples (10 plants/sample)	Treatment Plot Size (Longitude x latitude)	Plot	N Treatments (kg N/ha)	Volume SI Added (cm-ha)
SI Centrate + Water	2 | 2	4.6 x 15 m	2	N+: 300	30
			10	N++: 400	40
SI Urea + Water	2 | 2	4.6 x 15 m	4	N+: 250	2̲5
			6	N+: 250	2̲5
Non-SI Urea	2| 2	4.6 x 15 m	8	N+: 275	0
			12	N+: 275	0
Measured Check (No N)	5 | 5	3.0 x 15 m	3,5,7,9,11	0	0

The ends of each SI pipe were upended such that the system's only functional capacity was to add water to the water table. This was considered sufficient functionality for the purposes of the study—given that no drainage was present on the site prior to the study and the resources that were available. The nearest mapped drainage tile was located approximately 140 m to the west (Figure 16).

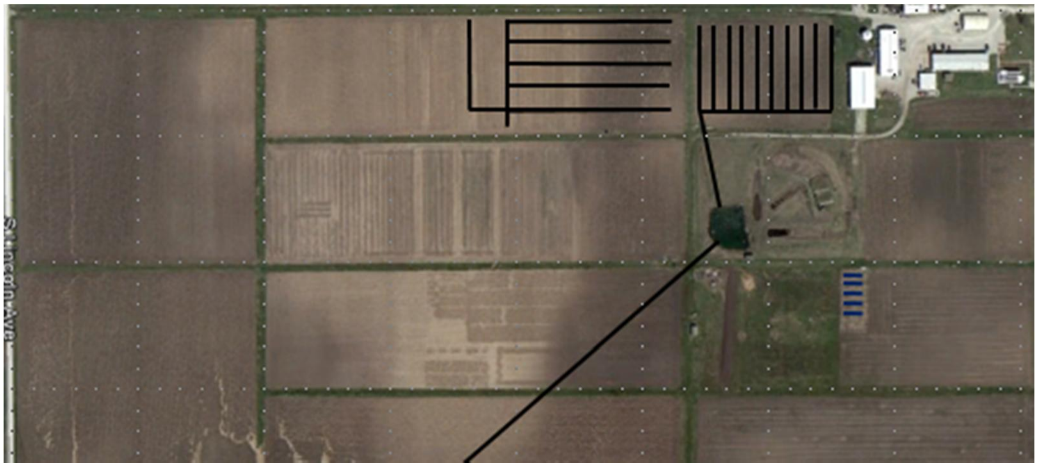


Figure 16. Drainage layout on Ag Engineering Farm (Black lines indicate drainage tiles. Blue lines indicate subirrigation tiles.)

The water delivery system to each SI pipe was gravity-fed with 4 tanks-3 of which had capacities of 1900 L. One tank had a capacity of 1600 L. These are shown on the following page.

Figure 17. 2013 water delivery system tanks

Figure 18. Junction between tank and 1.5 in ID hose

Each tank was adjoined with a flexible 1.5 in ID hose at its bottom (Figure 18). This hose delivered the treatments to each SI pipe.

The hybrid P35K09AM1 (1406 modified growing degree days Celsius ($MGDD_c$) to R6) was planted in 76 cm rows at a rate of 86,074 seeds/ha on June 28th.

The first application of centrate or urea through SI and urea applied topically (by hand) took place on August 7th, when the field was between the V6 and V8 stage. Corn roots were at approximately 50 cm, based upon soil water measurements in 2014 (Appendix). Full details of centrate characteristics can be found in Tables 38 in the Appendix.

The second application of treatments took place on August 15th. The corn was between V8 and V9. Corn roots were at approximately 59 cm and had access to nitrogen which was delivered through SI treatments at 60 cm.

The third application of treatments took place on August 20th when the corn was at approximately V11. No precipitation fell that would have stimulated hydrolysis of urea and move it into the soil. The corn roots were at approximately 69 cm. There was no visible difference among plants that reflected the nature of the treatments.

The fourth application of treatments took place on August 28th when the corn was at approximately R1. Corn roots were estimated to be at a maximum depth of 90 cm. A quantity of 0.03 cm of precipitation fell between August 20th and the 28th.

The fifth application of treatments took place on September 5th when the corn was at approximately R2. Corn roots were at their maximum depth of 100 cm. A quantity of 0.33 cm of precipitation was received between August 28th and September 5th.

Because N uptake slowed by September 5th (Figure 19), four applications of 3 cm of only water through SI were made on September 13th, 20th, 27th, and October 3rd and 10th.

The first hard freeze occurred on October 21st (-1.7°C). Plants were harvested on November 2nd. Corn experienced only 1272 MGDD_c out of the 1406 MGDD_c needed to reach R6.

Plant sampling and analysis will be described, beginning in the "Plant Sampling Procedure" section.

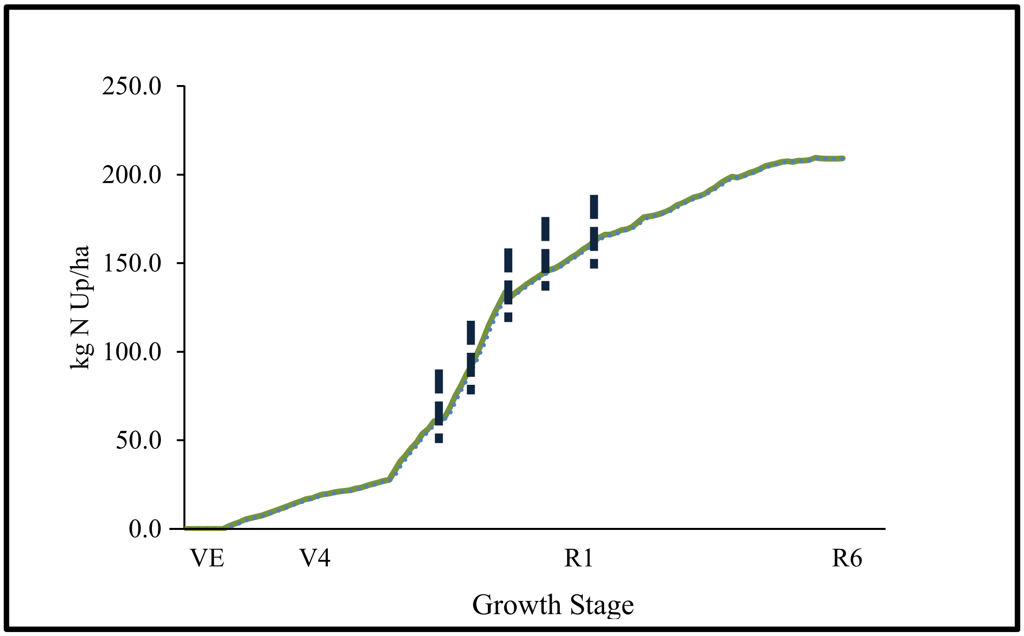


Figure 19. Approximate representation of SI-fertilization treatments during 2013 with respect to N uptake and plant maturity. This symbol (┇) represents a single SI-fertilization treatment. (Recreated from Bender, Haegele et al. 2012)

2014 Field Management (Full Fertilizer Management Details Can Be Found in Table 41 in the Appendix)

In April 2014, an additional field, located 200 m to the southwest was selected (Figure 11) in order to add a treatment that made SI applications without nitrogen. Both Non-SI treatments were moved to this field known as "Non-SI Field" in Table 14.

Table 13. 2014 plot design-SI Field

Treatment	**No. of Plots | No. of Samples (6 plants/sample)**	**Treatment Plot Size (Longitude x latitude)**	**Plot**	**N Treatments (kg N/ha)**	**Volume SI Added (cm-ha)**
SI* Centrate + Water (N+, N++)	2 | 30	4.6 x 12 m	2	N+: 390	12
			10	N++: 620	11
SI* Urea + Water (N+, N++)	2 | 30	4.6 x 12 m.	4	N+: 420	12
			6	N++: 610	12
SI* Water (Base N only)	1 | 15	4.6 x 12 m	8	Base N and Starter N: 190	12
Control (Base N only)	4 | 20	3.0 x 12 m	3,5,7,9	Base N: 140	0
***All* SI treatments received a starter 49 kg N-urea/ha on the surface on June 11 in addition to the Base N fertilization**					

Table 14. 2014 plot design-Non-SI Field

Treatment	**No. of Plots | No. of Samples (6 plants/sample)**	**Treatment Plot Size (Longitude x latitude)**	**Plots**	**N Treatment**	**Volume SI added (cm-ha)**
Non-SI Urea (N+, N++)	4 | 30	4.6 x 12 m	2,4	N+: 340	0
			6,8	N++: 650	0
Control (Base N only)	4 | 20	4.6 x 12 m	3,5,7	Base N: 140	0

The water delivery system was improved in order to ensure more precise delivery of treatments than in 2013. Pipes were cleaned using high pressure water in March. Pipes were shortened to only 12 m in length (Figure 20) in order to make treatment plot size more precise and consistent. Junctions were added to conduits between tanks and SI pipe inlets (Figure 21) in order to reduce the number of tanks on site.

Figure 20. Digging out and cutting of the SI pipes prior to planting

Figures 21 & 22. Redesigning of the water delivery system

A preemergent application of 2 L/ha Lumax and 7 L/ha Atrazine was applied on the morning of May 20th. Corn was planted in 76 cm rows at 88,298 seeds/ha in the afternoon of May 20th. An application of 49 kg N-urea/ha was made on June 11th to each SI treatment plot. Symptoms of nitrogen and phosphorus deficiency were increasingly observed across the SI field as plants matured.

Figures 23 & 24. Symptoms of phosphorus and nitrogen deficiency

Corn grew until approximately the V7 stage when severe crop damage (Figures 25 and 26) developed following a 2.1L/ha Liberty post-emergence application on June 23rd.

Figures 25 & 26 Damage from herbicide contamination

The fields were mowed, chisel-plowed, and replanted on July 7th with the hybrid FS 34TVRIB (1169 $MGDD_c$ to R6) at a rate of 88,298 seeds/ha. In order to address the symptoms observed in the previous crop's early growth and the approximate uptake of 50 kg N/ha in its first seven stages of growth, applications of DAP was made on July 17th which consisted of 70. kg N/ha and 78 kg P/ha. Applications of DAP were also made on August 8th and 18th which each consisted of 33 kg N/ha and 37 kg P/ha.

Figure 27. SI Field on August 11th

On August 20th, the first fertilization treatment was made to each of the plots on the SI field and Non-SI field. Corn was at approximately V8. Nearly 1.0 cm of precipitation had fallen within 7 days of the first urea application. In 2013, 44 days passed before precipitation exceeded 1.0 cm following the first urea application on the Non-SI treatments.

On August 28th, the second fertilization treatment was made to each of the plots on the SI field. Corn was at approximately VT.

On September 12th, the third and final fertilization treatment was made to each of the plots on the SI field. Corn was at approximately R3. Moderate to severe disease was prevalent present owing to cool, wet temperatures and consecutive seasons in corn (Figures 28 to 30).

Figures 28, 29, & 30. Common smut (left, August 19th), Grey leaf spot, North Corn Leaf Blight, Common Rust, and Southern Corn Leaf Blight (middle, October 14th), and Gibberella Ear Rot (right, October 14th)

Temperatures were very cool and wet compared to 2013. By the date of the first hard frost on November 2nd (-5°C), 43.7 cm of precipitation had fallen (17.3 cm in 2013) and 1065 MGDD_c were experienced (1272 MGDD_c in 2013). Plants were harvested on November 2nd.

2013 Plant Sampling Procedure

Ten plants were randomly selected and cut, approximately 4 cm from the surface, from the two center corn rows on November 1st. The plants' ears were removed and stover was weighed fresh before shredding with a commercial brush chipper (Vermeer BC600XL) from which a representative fresh stover subsample was collected for drying. All 10 plants' ears and stover were dried at 75°C for 10 days.

2014 Plant Sampling Procedure

SI Field

In order to increase the number of samples for each treatment and collect data on the effect of distance from the SI pipe on grain yield and nitrogen uptake, 15 blocks of 6 plants were marked and cut, approximately 4 cm from the surface on November 3rd. The plants' ears were removed and stover was weighed fresh before shredding with a commercial brush chipper from which a representative fresh stover subsample was collected for drying. All 10 plants' ears and stover were dried at 75°C for 20 days.

The 15 blocks in each treatment were marked according to locations extending the entire length of the treatment plot. Three lengths were marked at distances of 1.2 m to the north of each treatment pipe, 0 m, or directly over the SI pipe, and 1.2 m to the south of the SI pipe. Each length consisted of 5 blocks. Each block consisted of 6 plants (Figure 31).

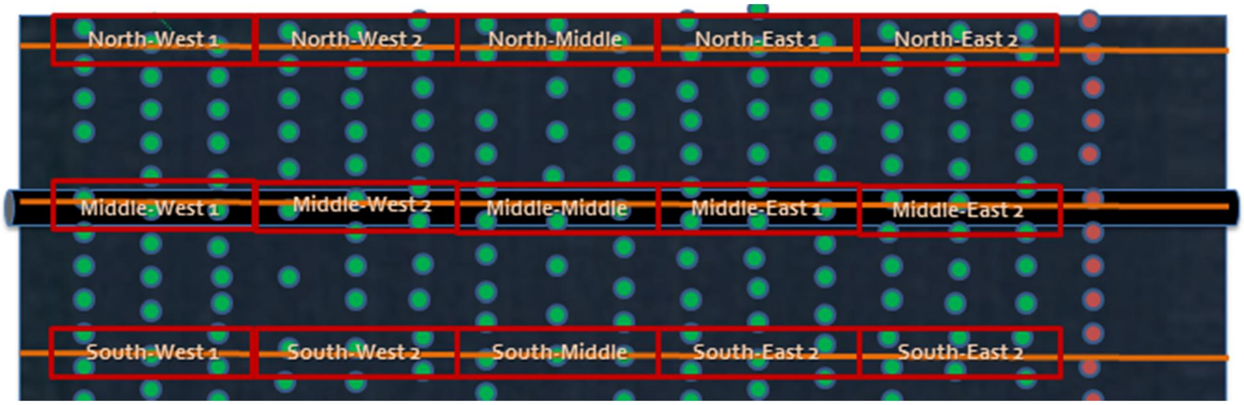
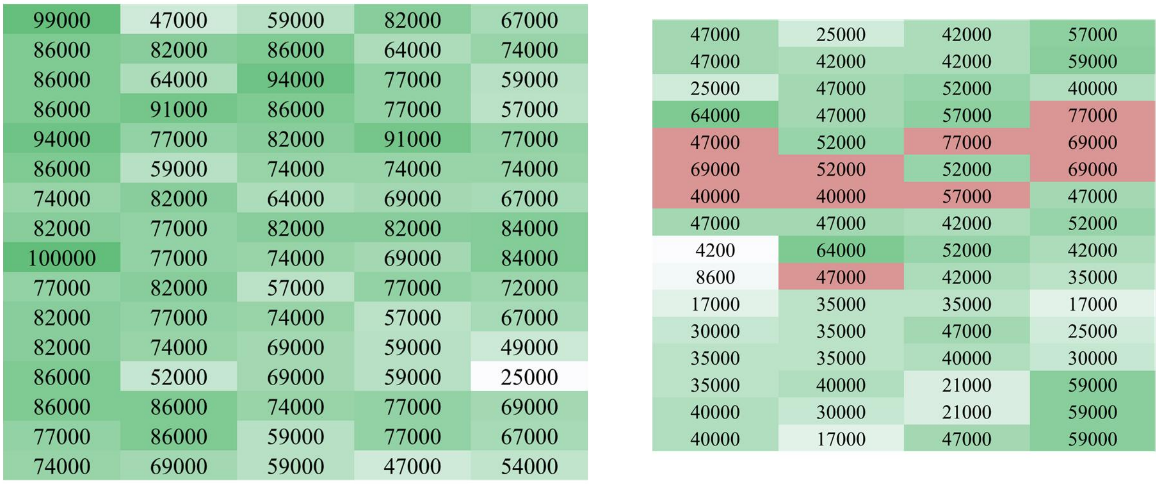


Figure 31. Treatment plot blocking

Non-SI Field

This field's sampling procedure did not involve blocking since treatment effect was assumed to be homogenous across each plot. In order to match the plant density for plant samples as closely as possible to that recorded in the SI field, plant density for each field was measured, estimated, and is displayed in the Figures 32 and 33.



99000	47000	59000	82000	67000
86000	82000	86000	64000	74000
86000	64000	94000	77000	59000
86000	91000	86000	77000	57000
94000	77000	82000	91000	77000
86000	59000	74000	74000	74000
74000	82000	64000	69000	67000
82000	77000	82000	82000	84000
100000	77000	74000	69000	84000
77000	82000	57000	77000	72000
82000	77000	74000	57000	67000
82000	74000	69000	59000	49000
86000	52000	69000	59000	25000
86000	86000	74000	77000	69000
77000	86000	59000	77000	67000
74000	69000	59000	47000	54000

47000	25000	42000	57000
47000	42000	42000	59000
25000	47000	52000	40000
64000	47000	57000	77000
47000	52000	77000	69000
69000	52000	52000	69000
40000	40000	57000	47000
47000	47000	42000	52000
4200	64000	52000	42000
8600	47000	42000	35000
17000	35000	35000	17000
30000	35000	47000	25000
35000	35000	40000	30000
35000	40000	21000	59000
40000	30000	21000	59000
40000	17000	47000	59000

Figures 32 and 33. Estimated plant density (plants/ha) at V10 in 204 for SI Field (left) and Non-SI Field (right.)

Lower emergence on the Non-SI field was likely a result of flooding and the creation of a hard pan from a precipitation event on July 13th of 11 cm and poorer drainage on the soil site (Champaign County Soil Survey, 2012; Google Earth, 2014). At sampling, rows were selected that most closely matched the average plant density on the SI field (74,000 plants/ha) and are highlighted in red.

2013 & 2014 Plant & Soil Sample Analysis

Grain Yield

Following ear drying, grain was mechanically removed, then weighed; masses were recorded for each 10 plant grain sample. Moisture was measured for each grain sample using a dielectric type grain moisture meter (SL95; Steinlite Corp.). Plot yield was estimated according to the following expression:

$$\frac{\boldsymbol{Grain\ sample\ mass}}{(\mathbf{1}-\boldsymbol{Grain\ sample\ moisture})} \div \frac{\boldsymbol{no.of\ plants/sample}}{\boldsymbol{no.of\ plants/ha}}$$

Equation 3. Calculation of plot yield

Grain protein concentration was measured using the Infratec© 1241 Grain Analyzer. Grain nitrogen concentration and content was then calculated by Equations 5 and 6 (Jones, Munsey et al. 1942)

$$\boldsymbol{Grain\ sample\ N\ concentration} = \boldsymbol{Grain\ sample\ protein\ concentration} * \mathbf{0.0625}$$

Equation 4. Calculation of grain nitrogen concentration

$$\boldsymbol{Grain\ sample\ N\ content} = \boldsymbol{Grain\ sample\ N\ concentration} * \boldsymbol{Grain\ sample\ mass}$$

Equation 5. Calculation of grain nitrogen concentration

Stover

After drying, stover sub-samples were ground in a Wiley mill to pass a 20-mesh screen. This dried sub sample was then used to analyze for stover total N using a combustion technique (EA1112 N-Protein; CE Elantech, Inc.). These measurements were then used to estimate stover production for each plot, total nitrogen uptake (Equation 6) and nitrogen uptake efficiency (Equation 7).

Soil Sampling & Analysis

Soil samples were removed at both sites (plants and no plants) on each of the treatment plots in 2013 on July 3rd and November 8th. Sample composites at two different depths—0 to 30 cm and 30 to 60 cm—each consisted of 4 cores. Cores were selected and removed at the 4 points of a diamond-shape pattern in the approximate center of each location within each treatment plot.

Samples were immediately dried at 75°C for 24 hours. Samples were then ground to pass through a 2 mm screen. Inorganic N analysis was performed using the accelerated diffusion methods described by Khan, Mulvaney, and Mulvaney (1997).

$$\boldsymbol{Stover\ \left(\frac{kg}{ha}\right) = \frac{mass\ of\ dried\ subsample}{mass\ of\ fresh\ subsample} * \frac{no.of\ plants/ha}{no.\ of\ plants/sample}}$$

$$\boldsymbol{Total\ nitrogen\ uptake = Grain\ N\ content +\ Stover\ N\ concentration * stover\ (\frac{kg}{ha})}$$

Equation 6. Estimation of total nitrogen uptake (NUp)

$$\boldsymbol{Nitrogen\ uptake\ efficiency = \frac{(treatment\ tot.N\ uptake - check\ tot.N\ uptake)}{quantity\ of\ N\ applied}}$$

Equation 7. Estimation of total nitrogen uptake efficiency (NUpE)

Statistical Analysis

Statistical analyses were performed using SAS 9.0 and Microsoft Excel 2010. Normality was assessed through Shapiro-Wilks in PROC UNIVARIATE and interaction of fixed effects were measured using PROC GLM (SAS 9.0). Tests of significance were performed with TTEST (Microsoft Excel 2010). One-tail and two-tail were each used as indicated. All variances were assumed to be unequal.

Assessing Nitrogen & Water Availability

Soil Profile Box

A demonstration of water movement away from a pipe in unsaturated conditions was performed according to the following “liquid”, volume, and time specifications. Each application corresponded to a field irrigation of 3 cm.

Table 15. Procedure for observing and recording water and nitrogen movement within the soil box

Liquid Applied	Volume Applied (L)	Date Applied	Application no.*	Time Intervals Recorded	Soil bulk density (g/cm^3)
Water	2	01/22/14	1	1, 2, 4, 8, 15, 30 min., 1, 2, 4, 24 hr.	1.61
	2	01/23/14	2	8, 15, 30 min., 1, 2.6, 4 hr.	
Water	2.17	01/25/14	1	8, 16, 32 min., 1, 2, 20 hr.	1.57 g/cm^3
Centrate	2.29	02/06/14	1	24 hr.	1.59 g/cm^3**
	2.38	02/08/14	2	24 hr.	
	2.37	02/09/14	3	24 hr.	

***"Application no." indicates the interval of application since the last time the soil profile was emptied, dried, and reconfigured.**

****estimate**

Following the conclusion of a given set of applications (i.e. "Water", on 01/22/14), the soil within the profile was emptied and dried down with a fan until completely air-dry (24 to 48 hours spread approximately 2 cm thick).

Centrate used for the experiment was collected on February 4, 2014 from the UCSD-NE WTP. Solids were moved by settling and transferring the decanted liquor to another container. Analysis of the NH_3-N concentration was performed using the High Range Ammonia Nitrogen AmVer^{TM} Salicylate Test 'N Tube Method (0.4 to 50 mg/L NH_3-N). Concentrations of the centrate are shown.

Table 16. Centrate NH_3-N concentrations during the soil profile box experiment

Date of Application (Application no.)	NH_3-N (mg/L)
02/06/14 (1)	320
02/08/14 (2)	310
02/09/14 (3)	280

Soil Sampling & Analysis

Soil samples were removed on February 10th, following the third application of centrate. Sample cores were removed at 4 locations surrounding the center of the SI pipe—defined by an x-y axis running through its center and marked in cm. These locations were the following: (0, 7.5), (19, 0), (0,-22), (-23, 0), (-7.5, 0), (0,-7). Soil samples were dried at 75°C for 24 hours, then ground to pass through a 2 mm screen. Ammonia-nitrogen analysis was performed using the accelerated diffusion methods of Khan, Mulvaney, and Mulvaney (1997).

CHAPTER 5: RESULTS & DISCUSSION

Weather, SI Events, and Water Table Height

In 2013, the growing period received only 46% of average precipitation levels. Corn in Champaign County yielded 8,900 kg/ha (USDA, 2015)—slightly below the average yield of 9,010 kg/ha since 2003 in Champaign County. Treatment plots that were subirrigated received 101% of the average precipitation for this growing period when natural rainfall was included. Temperatures were near average for the same period—just 0.2°C warmer than normal.

In contrast, in 2014, precipitation for the growing period was 13% above average. Corn in Champaign County yielded 11,500 kg/ha—(USDA, 2015) above the average yield of 9,010 kg/ha for 2003 to 2012. Plots receiving the sum of subirrigation and natural precipitation exceeded 139% of the water received from natural precipitation in this growing period which was approximately 100% of hybrid needs (Kranz, Irmak et al. 2008). Temperatures were 3.5°C cooler than normal. Tables 17 and 18 show temperature and heat unit data for the 2013 and 2014 growing seasons. Also included are the MGDD$_c$ required for each hybrid to reach physiological maturity (R6). These are shown in bold on the bottom right corner of each table below. Measured MGDD$_c$ from planting to harvest did not meet the hybrid requirement for MGDD$_c$ for planting to R6; in 2013 approximately 50 to 75% of the ears did develop a black layer in 2013. In 2014, no black layer was observed on grains.

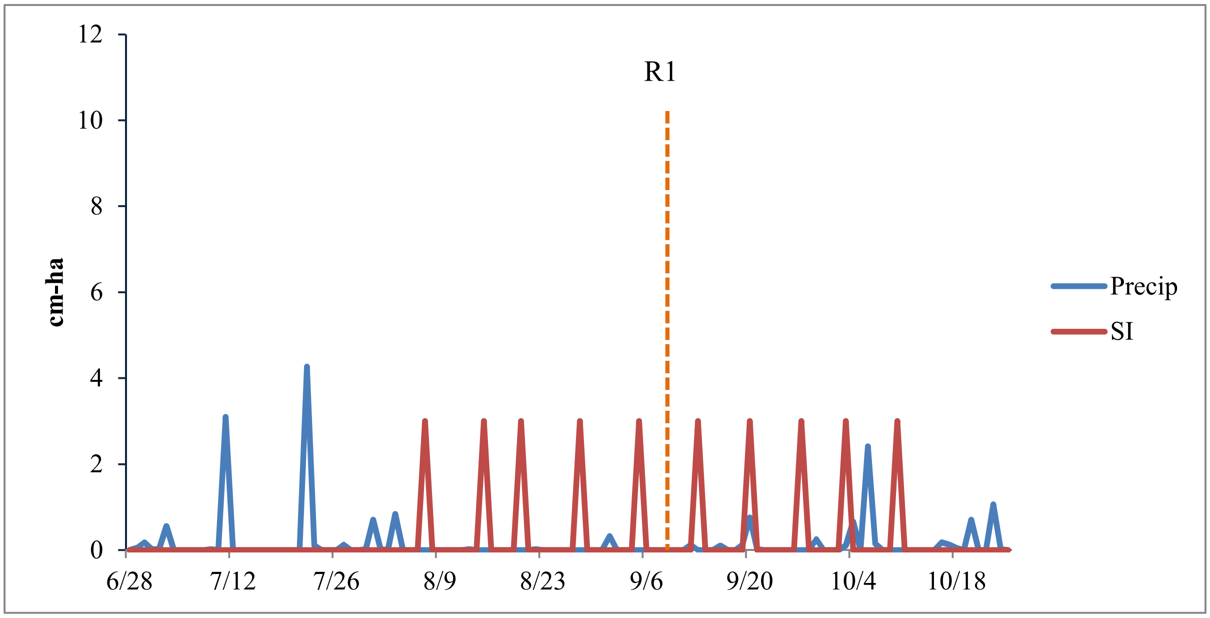


Figure 34. 2013 Quantities of precipitation & SI events (cm-ha)

Table 17. Daily high and low temperatures & heat units (MGDD$_c$)

2013	High/Low (ºC)	Avg	MGDD$_c$
Jun. 28-30	29.4/16.7	21.9	36
Jul.	33.1/9.4	22.5	381
Aug.	36.1/10.0	22.8	390
Sept.	36.1/7.2	20.9	322
Oct. 1-25	31.7/-3.9	13.3	143
	36.1 (+6.7)/ -3.9 (-9.8)	20.3 (+0.2)	1272
Parenthetical values indicate quantity above or below average conditions			

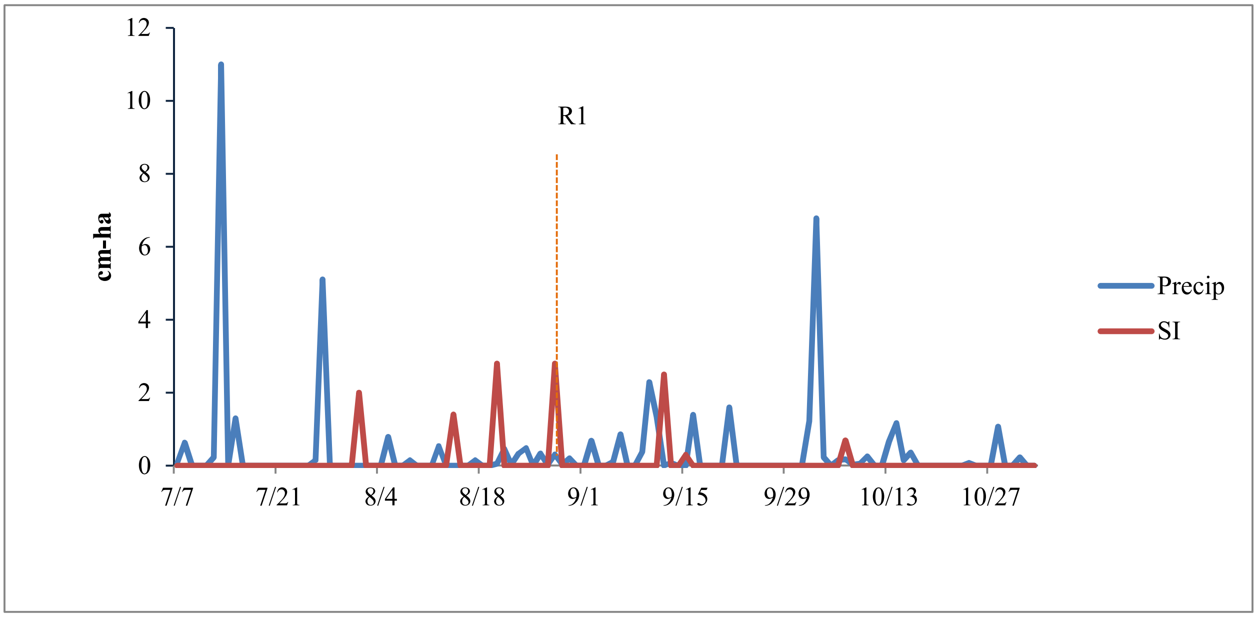


Figure 35. 2014 Quantities of precipitation & SI events (cm-ha)

Table 18. Daily high and low temperatures & heat units ($MGDD_c$)

2014	**High/Low**	**Avg**	**$MGDD_c$**
Jul. 7-31	31/12	21	279
Aug.	34/11.3	23	399
Sept.	34/4	18	256
Oct.	28/-1	12	130
Nov. 1-2	12/-5	3.3	1
	34 (+5.0)/ -5 (-10.9)	16 (-3.5)	1065

The study site's water table was shallow (Figure 36). In 2014, the water table on the SI field averaged 107 cm in depth during the growing season. The water table on the Non-SI field averaged 126 cm in depth during the growing season.

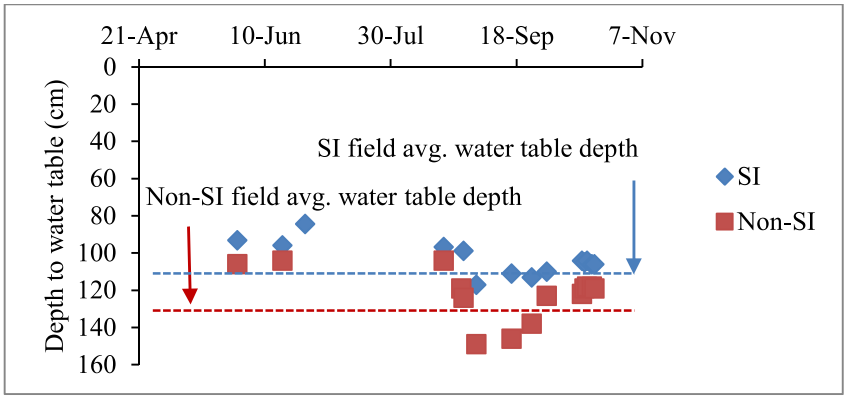


Figure 36. Water table depth during the 2014 growing season for each study field

2013 Grain Yield & Total Nitrogen Uptake Response Between Treatments

A single SI treatment, SICW N++ plot 10, responded 25% higher in grain yield and nitrogen uptake compared to other treatments (Figure 39). Even excluding this SI plot from the statistical analyses above, SI treatments' (SICW N+ and SIUW N++) grain yield was 8544 kg/ha—8% higher than the Non-SI treatments (p = 0.18, 1-tail) and 9% higher than the No N controls (p = 0.05, 1-tail). Average grain yield was 9076 kg/ha on all of the SI treatments which was 13% higher than the average grain yield of 7905 kg/ha on the Non-SI treatments (p = 0.08, 1-tail). Plots which received neither topical nitrogen as urea nor water through SI, yielded 7804 kg/ha which was 16% lower than the SI treatments (p = 0.05, 1-tail) and 1.3% lower than the Non-SI treatments (p = 0.43, 1-tail).

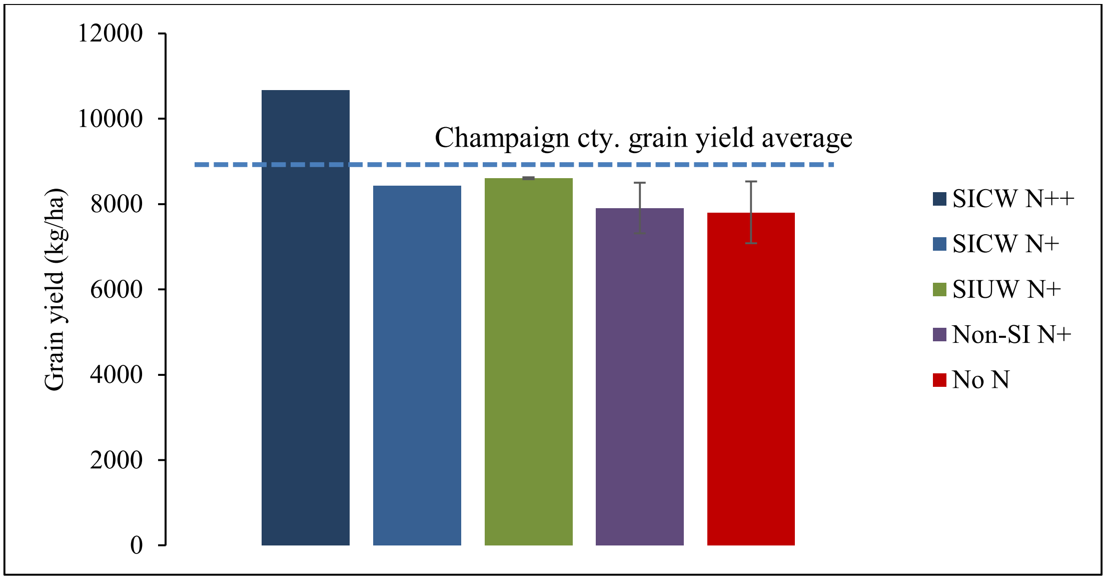


Figure 37. Grain yield among treatments

Nitrogen uptake followed the same pattern. Excluding SICW N++ on plot 10, average total nitrogen uptake was 2<u>0</u>0 kg N/ha on the SI treatments which was 8% higher than average total nitrogen uptake of 185 kg N/ha on the Non-SI treatments (p = 0.06, 1-tail). Plots which received neither topical nitrogen as urea nor water through SI, had an average total nitrogen uptake of 170 kg N/ha which was 18% lower than the SI treatments excluding SICW N++ ($p < 0.01$, 1-tail).

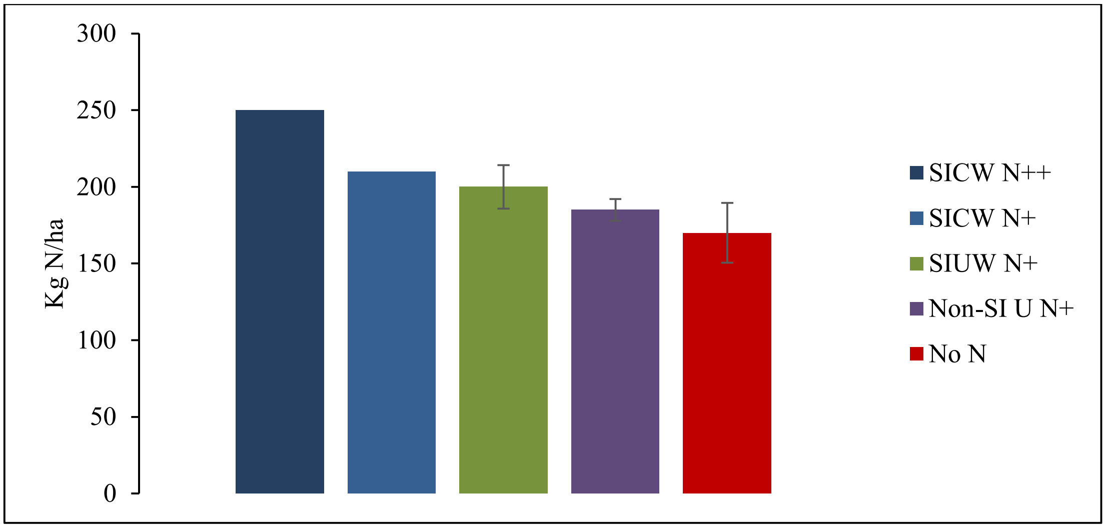


Figure 38. Total nitrogen uptake among treatments

The 2013 growing season was dry (Figure 34). For that reason, not only were SI treatments distinguished from Non-SI treatments in *where* they delivered nitrogen, but also *when* the nitrogen became available. Figure 34 shows the relationship between precipitation events and treatment events (represented by red spikes in the SI line because applications of topical urea on Non-SI coincided with SI events). While nitrogen became available to the plants on the SI treatments once roots reached SI's N delivery matrix, nitrogen became available only incrementally to Non-SI U treatments through the dissolution of topical urea during precipitation events. While Non-SI U treatments had the advantage of delivering N to the most active part of the roots (Mengel and Barber, 1974), they had the disadvantage of relying upon sufficient precipitation for penetration of urea-N into the soil.

2013 Grain Yield Between Plots

Among the SI treatments, grain yield was similar (Table 19) despite quantities of water and nitrogen delivered to each SI treatment plot over the growing season varying due to poorly-designed conduit equipment and incomplete planning to ensure consistent and precise water/centrate irrigation volumes for each plot.

Table 19. 2013 ANOVA tests

ANOVA, P > F (PROC GLM)	
Trait	All treatments
Grain yield	0.36
Nitrogen uptake	0.19

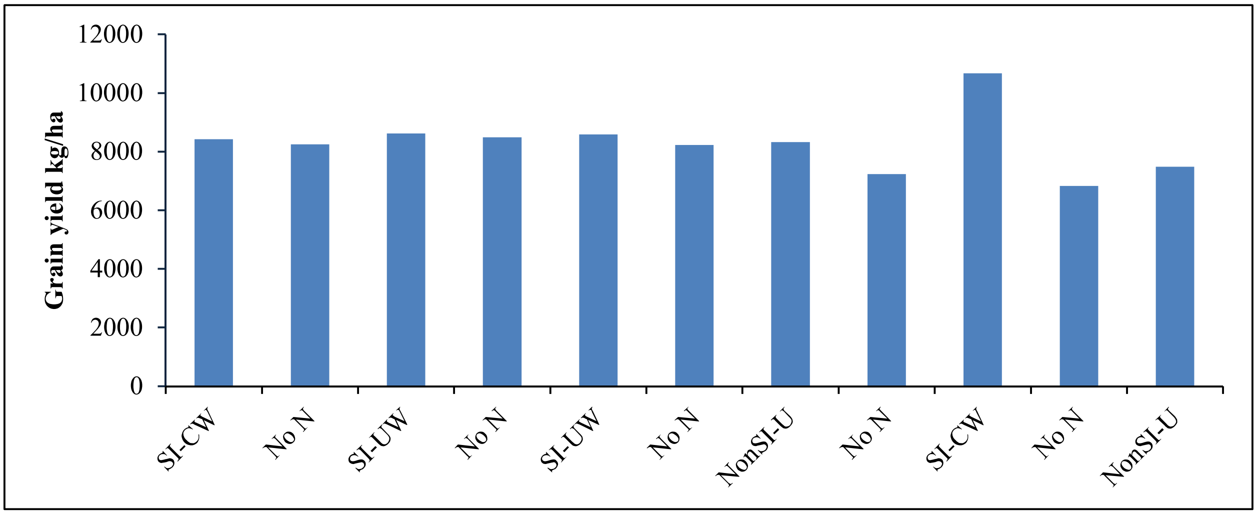


Figure 39. 2013 grain yield

Table 20. 2013 grain yield

Plot	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Trt	**SI-CW**	**No N**	**SI-UW**	**No N**	**SI-UW**	**No N**	**Non-SI U**	**No N**	**SI-CW**	**No N**	**Non-SI U**
Yield (kg/ha)	8424	8246	8622	8484	8587	8225	8323	7231	10670	6832	7486
App. Tot. N	300	0	250	0	250	0	275	0	400	0	275

Each weekly SI treatment between August 7th and October 10th was intended to deliver 760. L of water to each plot (3.0 cm-ha). Approximately 5% of each weekly application was lost from each of the SI plots (2, 4, 6, and 10). Further, an additional 10% of the 760. L was lost on plot 4 SIUW at each SI event due to leakage in a junction between 2—380 L water tanks. Approximately 5% of each weekly application was lost from Plot 10 SICW as well; however, an imprecise strategy for water delivery with this tank, resulted in approximately 15% greater than 760. L of water to be delivered each week. These variations appeared to have made only a small impact in distinguishing grain yield on one SI treatment from another (Table 20).

Table 21. 2013 ANOVA Tests

ANOVA, P > F (PROC GLM)	
Trait	SI treatments
Grain yield	0.49

Plot 10 SICW yielded 25% higher than the average of all SI treatments (8544 kg/ha). The additional grain yield boost was likely caused by excess N which was also supplied through the same faulty design and planning described earlier (approximately 33% more than the average N rate on the other SI treatments). Second, a contributing factor may have been 36% higher soil N_{min} in the 30 to 60 cm zone than the field average (Figure 41)—a factor which will be discussed further in later sections along with how this affected yield and nitrogen uptake.

2013 Nitrogen Uptake Between Plots

Centrate was utilized as well as urea as a nitrogen source when delivered through SI; nitrogen uptake efficiencies were similar between SICW than SIUW ($p = 0.39$, 2-tail). The lowest nitrogen uptake efficiencies were observed on plots 8 and 12 (Non-SI U). Nitrogen that was applied on the surface as urea was considered not plant available until at least 0.6 cm of precipitation fell. The only precipitation event greater than 0.03 cm occurred after 3 fertilization treatments had been made to each of the plots—0.33 cm. SI and topical urea application events with respect to precipitation events for 2013 are shown in Figure 34. Note that each SI event represented by a sharp spike in the red line) coincided with a topical urea application for each of the Non-SI plots.

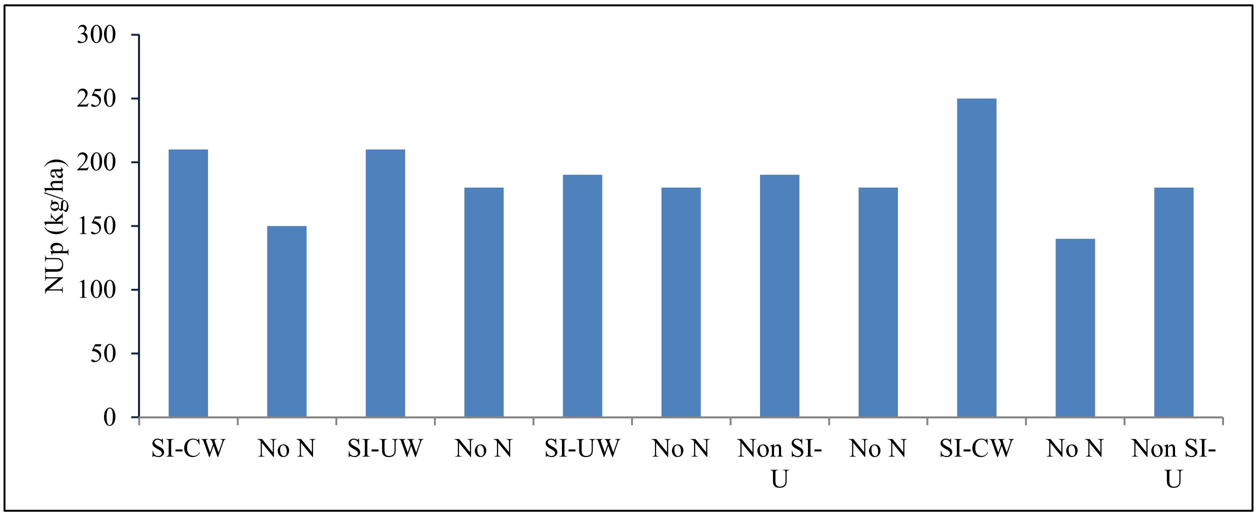


Figure 40. 2013 Total nitrogen uptake

Table 22. 2013 Total nitrogen uptake

Trt	**SI-CW**	**No N**	**SI-UW**	**No N**	**SI-UW**	**No N**	**Non SI-U**	**No N**	**SI-CW**	**No N**	**Non SI-U**
NUp kg/ha	210	150	210	180	190	180	190	180	250	140	180
NUpE	0.12		0.13		0.065		0.071		0.26		0.036
App. N kg/ha	300		250		250		275		400		275

The quantity of nitrogen assimilated was a function of plant emergence, root growth, SI pipe depth, method in which nitrogen was applied, precipitation, hybrid, heat available (measured in $MGDD_c$), and native soil N_{min}. Considering these parameters, the following predictions were made with respect to total nitrogen uptake in 2013 for each treatment plot.

Root growth was estimated using soil moisture depletion data provided by Bender (unpublished data, 2014. Urbana, IL: University of Illinois) for a site just 2 km to the north of the site in this study (see Appendix), with a hybrid with an equivalent relative maturity to the hybrid used at this site (113 d), and planted only 5 days earlier in the season than the site in this study

(June 23rd, 2014). The most significant distinction between this soil moisture data set were temperatures and precipitation in 2013 versus 2014. Because root growth is stimulated largely by water availability and water was less available in 2013, the application of this data may have predicted slightly slower root growth than was actually observed for this study.

Nitrogen uptake rates as a function of genetic potential was estimated by Bender, Haegele et al. (2012).

Precipitation was used to estimate topical urea dissolution—assuming 30 kg N-urea/ha was dissolved with each 0.2 cm of rain.

Modified growing degree days were used to estimate nitrogen uptake as a function of metabolic activity.

Nitrogen uptake rates in the growth cycle were categorized into one of three stages—early vegetative, late vegetative, and reproductive. Each stage was represented according to the following base formulas (Table 23).

Table 23. Estimation of nitrogen uptake rates for each growth period

Nitrogen uptake stage	**Days (since planting)**	**Total nitrogen uptake =**
Early vegetative	8 to 37	0.067 kg N/$MGDD_c$ * 170/286 * $MGDD_c$ recorded
Late vegetative	38 to 59	0.27 kg N/$MGDD_c$ * 170/286 * $MGDD_c$ recorded
Reproductive	60 to 119	0.082 kg N/$MGDD_c$ * 170/286 * $MGDD_c$ recorded

Constants for each stage were calculated according to measurements from Bender, Haegele et al. (2012).

The fraction, 170/286, represents the relationship between the genetic potential for N uptake and the limitation of soil N_{min}. In Bender, Haegele et al. (2012), nitrogen was considered to be non-limiting based upon the nature of the study and the values observed and so "286" represents the quantity of nitrogen assimilated by the hybrid used in this study should it have been non-limiting. The value "170" represents the total N assimilated on the no nitrogen treatment plots—assuming that no other differences between the Bender study and this one were significant. In summary, this fraction represents the degree to which N was limited for each treatment plot until roots reached the N delivery matrix or sufficient precipitation fell to dissolve topical urea. Based upon these considerations, the following predictions were made for each treatment plot.

Table 24. Modeled relationship between MGDDc, N delivery, root growth, and pipe depth

Plot	Trt	Predicted kg N/ha assimilated	Kg N/ha assimilated
2	SICW	210	210
4	SIUW	210	210
6	SIUW	210	190
8	Non-SI	175	190
10	SICW	210	250
12	Non-SI	170	180

As shown, the relationship between precipitation, pipe depth, heat, date of emergence, date of fertilization events exactly accounts for N uptake observations on 2 of the 6 treatment plots.

See Figure 41 for the relationship which was observed between starting soil N_{min} in the 30 to 60 cm zone, predicted N uptake (Table 24), and observed N uptake. Three of the 6 plots demonstrated higher than predicted total plant N uptakes—plots 8, 10, and 12. Plots 10 and 12 both started with soil N_{min} concentrations which were 36 and 33% above the field average (14 mg soil N_{min}/kg soil).

This same pattern is also observed in plot 6 SIUW which assimilated less N than predicted and also showed the lowest soil N_{min} concentrations at 30 to 60 cm among all treatment plots.

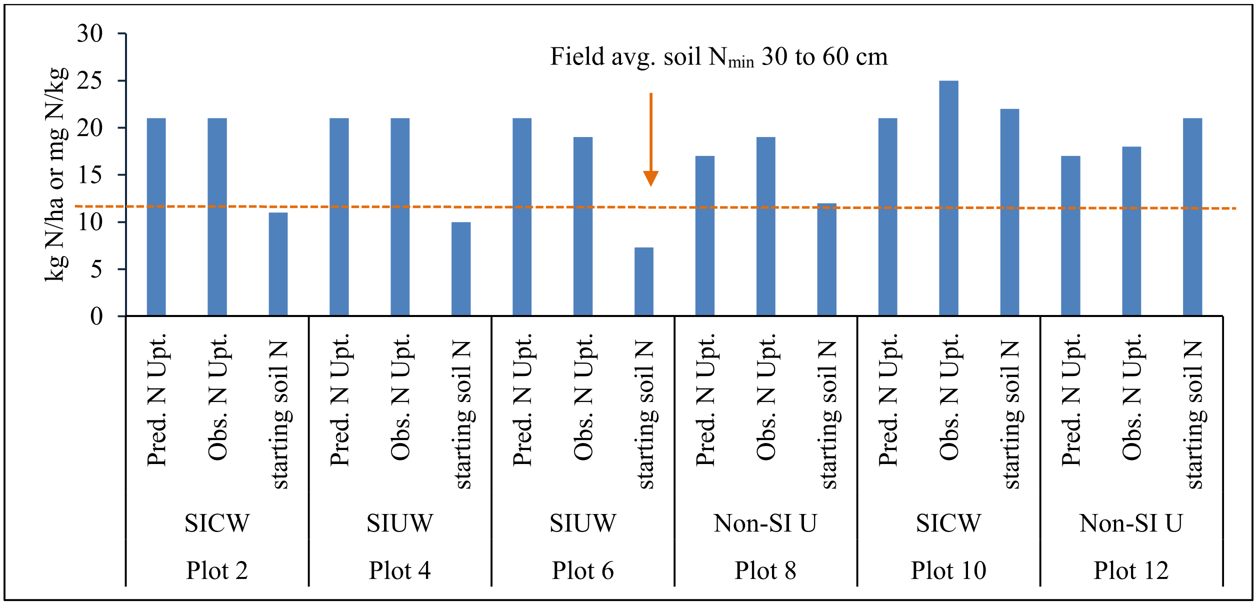


Figure 41. Relationship between predicted N uptake, observed N uptake, and starting N_{min} for 30 to 60 cm (July 3rd, 2013)

The relationship between soil N_{min} at the 30 to 60 cm zone and total nitrogen uptake is critical for the reason that it was in this stage that N uptake rates were high during the early part of the late vegetative stage, but SI and Non-SI treatments had not become factors. For that reason, soil N_{min} at this depth, at this stage, was the critical differentiating factor.

While nitrogen was non-limiting once delivered through SI (Peng, Yu et al. 2013), work by Chen, Zhang et al. (2010) demonstrated that, even above non-limiting soil concentrations, enhanced applications of nitrogen can enhance growth and concentrations within the plant. This was evidenced where, not only did SICW plot 10 respond with the highest nitrogen uptake, but a high N concentration in the stover as well among the SI treatments while maintaining a high N harvest index (Table 25).

Table 25. The relationship between stover N concentration and N harvest index

Plot	Treatment	Stover N concentration (%)	N Harvest Index
2	SICW	0.77	0.69
4	SIUW	0.73	0.65
6	SIUW	0.87	0.68
8	Non-SI U	0.73	0.65
10	SICW	0.83	0.70
12	Non-SI U	1.06	0.64

Because no treatments included only water treatments through SI, no conclusions can be made regarding the independent roles of water and nitrogen each in 2013; however, based upon the more significant effects of SI on nitrogen uptake on grain yield, it is likely that nitrogen was more efficiently delivered than water to corn roots in 2013.

Summary of 2013 Results:

- Grain yield and nitrogen uptake were enhanced by 13% ($p = 0.08$, 1-tail) and 14% ($p = 0.05$, 1-tail) on SI compared to Non-SI treatments, respectively
- Centrate were equally effective as a nitrogen sources when delivered through SI ($p = 0.39$, 2-tail)

- The benefits of a high N delivery strategy contributed to 25% higher N uptake on plot 10 SICW

2014 Grain Yield & Total Nitrogen Uptake Response Between Subirrigation & Non-Subirrigation

Average grain yield followed a similar pattern as 2013 (Figure 42). On the SI treatments, average grain yield was 5940 kg/ha, which was 20% higher than the average grain yield of 4970 kg/ha on the Non-SI treatments ($p = 0.05$, 1-tail). Control plots which received only the base application of N of 140 kg/ha topical nitrogen as urea nor water through SI, yielded 4590 kg/ha which was 29% lower than the SI treatments ($p < 0.01$, 1-tail) and 4% lower than the Non-SI treatments ($p = 0.05$, 1-tail).

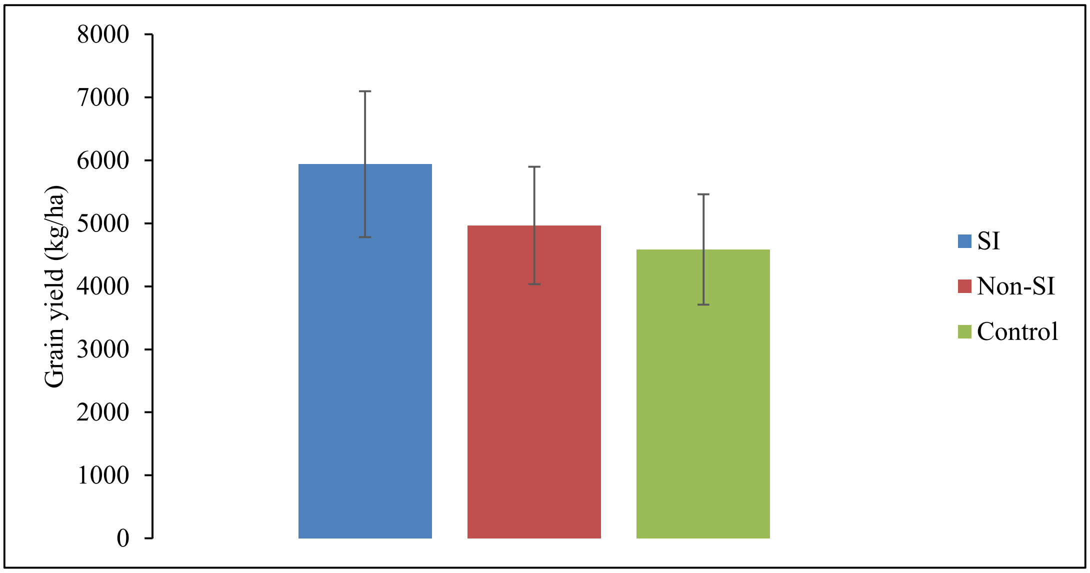


Figure 42. Grain yield with respect to SI, Non-SI, and Control

Total nitrogen uptake did not show the same relative pattern as 2013. Non-SI plots showed the highest average total nitrogen uptake—140 kg N/ha, which was 8% higher than average total nitrogen uptake of 130 kg N/ha that was recorded for the SI plots ($p = 0.31$, 1-tail). Control plots' average total nitrogen uptake was 110 kg N/ha which was 18% lower than the average total N uptake on the SI treatments ($p < 0.01$, 1-tail) and 29% lower than the average total N uptake on the non-SI treatments ($p < 0.01$, 1-tail). Plots which received neither topical nitrogen as urea nor water through SI, had an average total nitrogen uptake of 110 kg N/ha which was 18% lower than the SI treatments ($p = 0.01$, 1-tail) and 27% lower than the Non-SI treatments ($p = 0.06$, 1-tail).

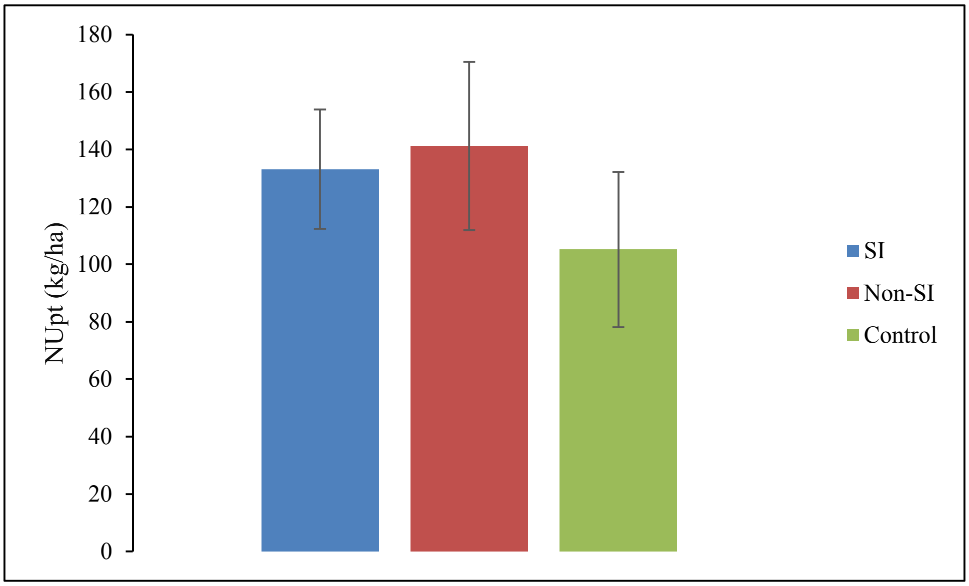


Figure 43. Total nitrogen uptake with respect to SI, Non-SI, and Control

In 2013, only 7.26 cm of precipitation fell on the 80 days between the first application of topical urea and harvest (Figure 34). In 2014, 21.89 cm of precipitation fell on the 68 days between the first application of topical urea and harvest. Further, in 2013, six days passed before any precipitation fell after the first application of topical urea—even then, this was only 0.03 cm. In 2014, however, 0.03 cm of precipitation fell on the same day of application and 1.24 cm of precipitation fell within 7 days of the first application of topical urea. Because of this difference between 2013 and 2014, added nitrogen was immediately available to plant roots in 2014. For the SI plots, nitrogen did not become available until roots had reached the nitrogen delivery zone.

2014 Grain Yield & Total Nitrogen Uptake Response Among Subirrigation & Non-Subirrigation Treatments

In contrast with 2013, grain yield did vary significantly among the treatments and so did total nitrogen uptake (Table 27 and Figure 44 on the following page).

The method in which nitrogen was delivered (SI or Non-SI) did not have a significant benefit to enhancing nitrogen uptake ($p = 0.31$, 1-tail). In contrast, in 2014, NUptE on Non-SI U plots were less likely to be dissimilar from SI treatments ($p = 0.63$, 2-tail). This difference accounts for higher nitrogen uptake rates on SI treatments than Non-SI treatments in 2013 and the opposite result in 2014. Interestingly, grain yield was still higher on SI treatments ($p = 0.05$, 1-tail) despite this difference. This result supports the hypothesis that water, not just nitrogen, helped support higher grain yields and nitrogen uptakes.

Table 26 ANOVA tests for 2014

ANOVA, P > F (PROC GLM)	
Trait	Treatments
Grain yield	0.02
Nitrogen uptake	0.02

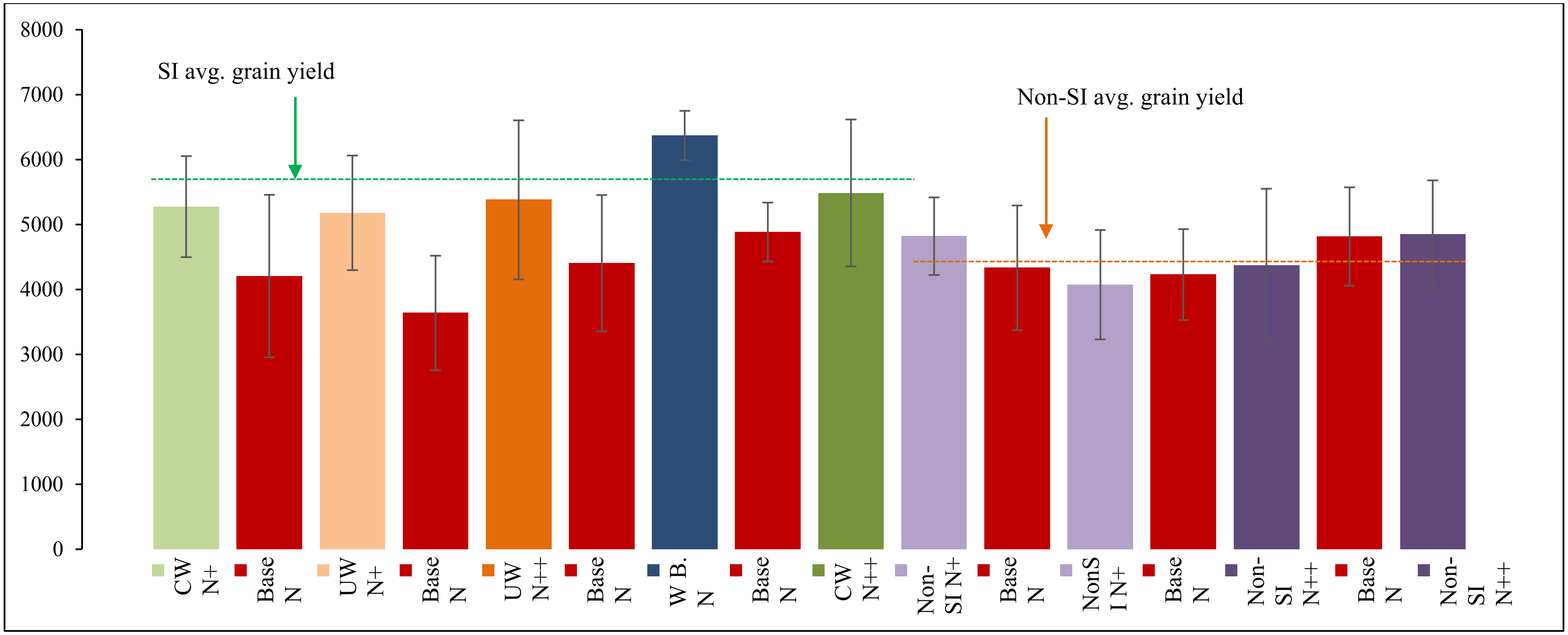


Figure 44. 2014 grain yield

Table 27. 2014 grain yield

	SI Field									Non-SI Field						
Plot	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Trt	**CW N+**	**Base N**	**UW N+**	**Base N**	**UW N++**	**Base N**	**W Base N**	**Base N**	**CW N++**	**N+**	**Base N**	**N+**	**Base N**	**N++**	**Base N**	**N++**
Grain yield	5280	4210	5180	3640	5380	4410	6370	4880	5480	4820	4330	4070	4230	4370	4820	4850
App. N kg/ha	390	140	420	140	610	140	190	140	620	340	140	340	140	650	140	650

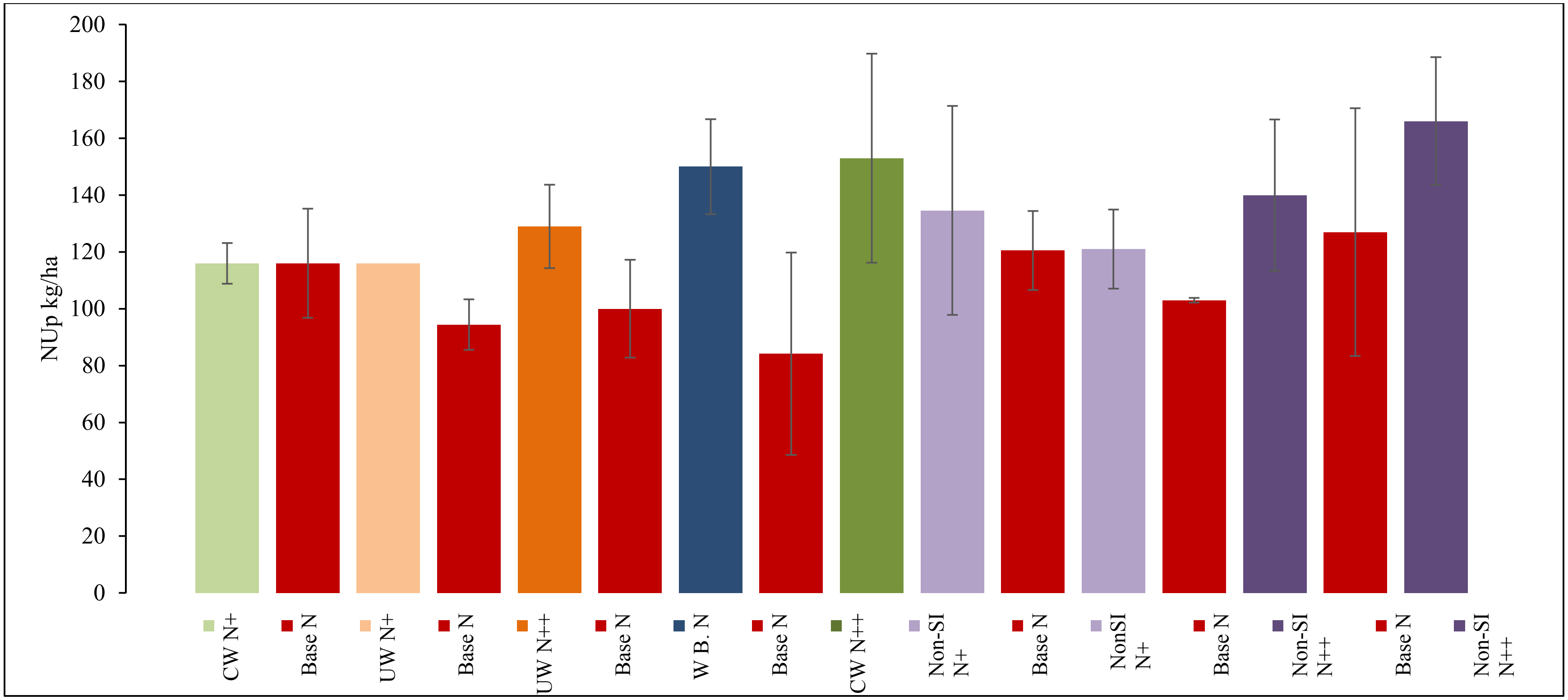


Figure 45. 2014 Total nitrogen uptake

Table 28. Total nitrogen uptake

	SI Field									Non SI Field						
Plot	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Trt	**CW N+**	**Base N**	**UW N+**	**Base N**	**UW N++**	**Base N**	**W Base N**	**Base N**	**CW N++**	**N+**	**Base N**	**N+**	**Base N**	**N++**	**Base N**	**N++**
Upt N kg/ha	116	116	116	94.4	127	100	150	84.2	153	135	128	120	103	140	127	166
NUptE	.044		.040		.050		3.0		.10	.062		.072		.075		.12

2014 Grain Yield & Total Nitrogen Uptake Response to High Nitrogen Treatments

Recall that an important element of an efficient model for utilizing centrate for corn production was minimizing the land space requirement. As such, treatments were added in 2014 that included nitrogen rates substantially higher than that typically applied (Table 29). These treatments are distinguished by the following notation:

Table 29. Explanation for N treatment notation

Notation	Description
Base N	140 kg N/ha, includes DAP applications prior to and early in 2014 growing season to address N and P deficiencies
N+	N rate which was 1 level higher than Base N, representative quantity varied among treatments
N++	N rate which was 2 levels higher than Base N, representative quantity varied among treatments

SI treatments which were fertilized by nitrogen over 2 times the typical quantity assimilated (Bender, Haegele et al. 2012) showed 21% higher N uptake compared to those fertilized by nitrogen approximately 1.5 times the typical quantity assimilated ($p = 0.07$) and 27% higher than those fertilized at the controlled rate ($p < 0.01$).

The same pattern was observed, though not as significantly, on the Non-SI field where those fertilized by nitrogen over 2 times the typical quantity assimilated 15% more kg N/ha compared to those fertilized by nitrogen approximately 1.5 times the typical quantity assimilated ($p = 0.03$) and 38% more than those fertilized at the controlled rate ($p < 0.01$).

Unexpectedly though, the second highest N uptake for a treatment was observed on plot 8 SIW. The 2014 growing season involved the addition of a SI treatment that received no nitrogen through SI—SI W, plot 8. The purpose of this treatment was to distinguish the effect of nitrogen added through SI from the effect of water added through SI. It yielded 6370 kg/ha which was 20% higher than the SI treatments which did receive nitrogen through SI (SIUW & SICW on Plots 2, 4, 6, and 10) (p = 0.010). Nitrogen uptake for this plot averaged 150 kg N/ha. This plot did not even receive nitrogen through SI and yet responded with the highest N uptake of any treatment. This is most likely explained by the strategy to move all Non-SI treatments to another field located 200 m to the southwest. Recall that plot 8 in 2013 was a Non-SI U treatment with a low NUptE—meaning a substantial quantity of N_{min} would have remained in the upper 60 cm of the soil. This hypothesis is confirmed by soil N_{min} tests from the end of the growing seasons (Figure 46).

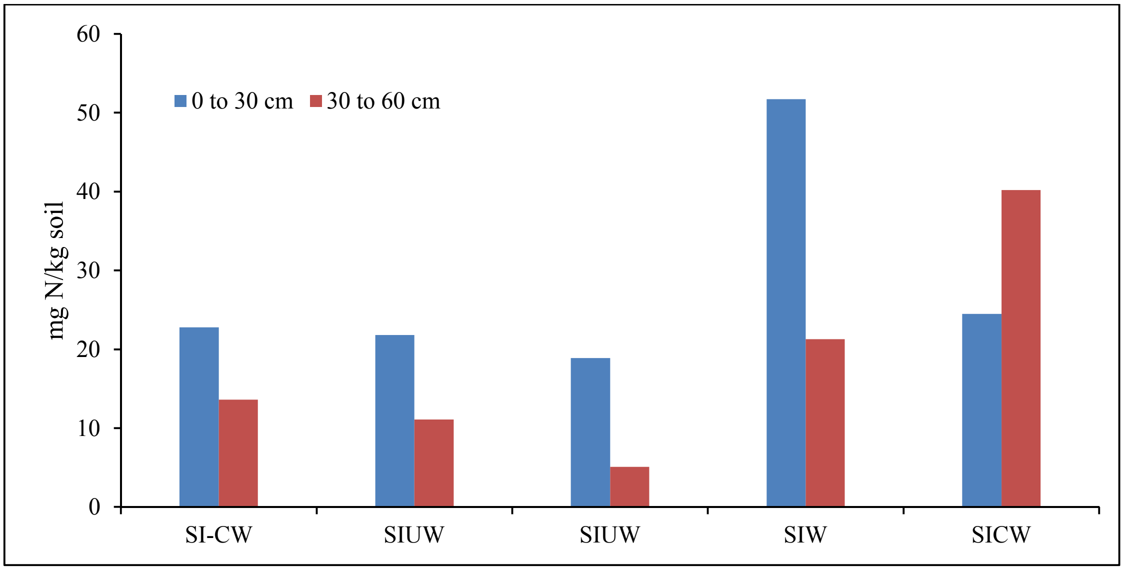


Figure 46. Inorganic soil N, measured on November 2nd, 2013

As shown, soil mineral nitrogen at the 0 to 30 cm depth was 66% higher on 2014's Plot 8 SIW (Plot 8 Non-SI U in 2013) compared to each of the other SI treatment plots.

As in 2013, centrate was used as efficiently as urea when delivered through SI (Table 28)—NUptE averaged 0.081 kg N/kg treatment N on the SICW plots while it averaged 0.048 kg N/kg treatment N on the SIUW plots ($p = 0.31$).

Comparing 2013 to the 2014 Growing Season

The differences among treatments within growing seasons have already been discussed; however, the absolute values for grain yield and nitrogen uptake, for all treatments were substantially lower in 2014 (Table 30). The causes for these differences are summarized in Table 32.

Table 30. Comparing grain yield and total nitrogen uptake

	Grain Yield (kg grain/ha)			**Total nitrogen uptake (kg N/ha)**		
	SI	**Non-SI**	**Control**	**SI**	**Non-SI**	**Control**
2013	9076	7905	7804	215	185	170
2014	5940	4970	4590	130	140	110

Table 31. Yield limiting conditions in 2014, environmental

	Environmental yield-limiting conditions				
	$MGDD_c$ to R6	**Previous crop**		**Planting date**	**$MGDD_c$ exp./$MGDD_{c\ R6}$**
		SI Field	**Non-SI Field**		
2013	1406	Corn, 1 season	NR	June 28	.91
2014	1169	Corn, 2.5 seasons	Corn, 1.5 seasons	July 7	.91

Table 32. Yield limiting conditions in 2014, disease

	Yield-limiting conditions, disease				
	Grey Leaf Spot	**Northern Corn Leaf Blight**	**Common rust**	**Gibbrella ear rot**	**Southern Corn Leaf Blight**
2013	Mild to moderate	Mild	None obs.	None obs.	None obs.
2014	Moderate to severe	Moderate to severe	Mild to moderate	Mild	Mild to moderate

The hybrid planted in 2014 required 20% less MGDDc (1169) needed to reach maturity and was planted 12 days later from the one used in Bender (unpublished data, 2014. Urbana, IL: University of Illinois) study. Further, precipitation in 2013 over the whole growing season was only 40% of what was observed in 2014. For that reason, less and slower root growth would have been expected, as compared to what was observed in 2013. Lastly, in 2014, prior to the first SI treatment of nitrogen, all SI and non-SI plots had received at least 136 kg N/ha. Symptoms of nitrogen and phosphorus deficiency across the fields were significant (Figures 23 & 24).

The SI field was in its third consecutive season for corn. The Non-SI field was in its second consecutive season. Both fields had also been planted to corn on May 20th with the hybrid P1221AMXT at 88,298 seeds/ha. It grew to approximately V7—assimilating approximately 50 kg N/ha before herbicide contamination (Figures 25 & 26).

Grain Yield & Total Nitrogen Uptake Response with Distance from the SI Pipe

To this point, discussion for both growing seasons has been with respect to grain yield and nitrogen uptake directly over the SI pipe. Limited resources and planning resulted in data collection for only the SI pipe. The 2014 growing season also saw the addition of recording yield and nitrogen uptake as distance from the SI pipe changed. The response of grain yield to distance from the pipe is shown below.

Table 33. Grain yield with respect to distance from the SI pipe (Standard deviations are shown in parentheses)

Grain yield (kg/ha)				
		Distance from SI Pipe		
Treatment	Plot	0 m	1.2 m	4.6 m
SICW N+	2	5270 (779)	4705 (1500)	4210 (498)
SIUW N++	4	5180 (1220)	4680 (1220)	3640 (381)
SIW Base N	8	6360 (965)	5440 (725)	4880 (502)
SICW N++	10	5510 (1240)	5260 (1350)	ND
All		5940 (1160)	5050 (1150)	4460 (905)

SI treatments where grain yield directly over the pipe was recorded yielded 15% greater than yield 1.2 m away from the SI pipe ($p = 0.02$) and 25% greater than yield 4.6 m away from the SI pipe ($p < 0.01$).

The response of nitrogen uptake with respect to distance from the pipe is shown on the following page.

Table 34. Total nitrogen uptake with respect to distance from the SI pipe

Total nitrogen N uptake (kg/ha)				
Treatment	Plot	0 m	1.2 m	4.6 m
SICW N+	2	116 (7.16)	142 (44.1)	116 (13.5)
SIUW N+	4	116	104 (27.8)	94.4 (8.87)
SIUW N++	6	129 (14.6)	127 (18.6)	100 (17.2)
SIW Base N	8	150 (16.7)	124 (21.3)	84.2 (35.6)
SICW N++	10	153 (36.9)	127 (44.6)	ND
All		118 (49.2)	114 (41.5)	100 (47.1)

Total nitrogen uptake showed a similar pattern as grain yield. Directly over the SI pipe, nitrogen uptake was the highest at 118 kg N/ha. At a distance of 1.2 m away from the pipe, average N uptake was 114 kg N/ha. At 4.6 m from the SI pipe, average N uptake was 100. kg N/ha. There was no significant difference in nitrogen uptake between the 0 m distance and the 1.2 m distance ($p = 0.41$); however, nitrogen uptake was significantly higher for plants 1.2 m away from the SI pipe than 4.6 m away ($p <0.01$).

This distinctive pattern demonstrates that water and nitrogen were both effectively supplied to plant roots through this SI system. Water was the strongest effector of plant response—resulting in the highest grain yield directly over the SI pipe (5940 kg/ha) compared to just 1.2 m away (5050 kg/ha) ($p = 0.02$) and higher grain yield at the 1.2 m distance than the 4.6 m distance (4460 kg/ha, $p < 0.01$). Nitrogen effected a plant response through higher nitrogen uptake rates as distance from the SI pipe became less. Significantly higher nitrogen uptake was not observed directly over the pipe compared to 1.2 m away ($p = 0.41$); but, significantly higher nitrogen uptake was observed 1.2 m away than 4.6 m away from the SI pipe ($p < 0.01$).

Assessing Nitrogen & Water Movement

This difference—where grain yield was more strongly differentiated at each of the distances from the pipe than total nitrogen uptake—can be partly explained by a starter application of 49 kg N-urea/ha for all SI treatment plots on June 11th. This would have homogenized the response of grain yield and nitrogen uptake at 0 and 1.2 m away from the pipe—but particularly the nitrogen uptake response. Further, NH_3-N was more limited in the mechanisms through which it could move through the soil than was water (Bray, 1942). An experiment performed with the soil profile box described in the Materials & Methods helped demonstrate this (Figures 14 & 15). Starting soil conditions represent soil prior to 2 applications of 3 cm of centrate.

Table 35. Movement of water and ammonical nitrogen with respect to distance and location from the SI pipe

Position	x	y	NH_4-N (mg/kg)	H_2O (cm^3/cm^3)
Starting soil	ND	ND	26.2	0
A	0	7.5	25.9	0.14
B	19	0	39.0	0.13
C	0	-22	18.2	0.14
D	-23	0	35.8	0.12
E	-7.5	0	ND	0.15
F	0	-7	734	0.18
G	7.5	0	128	0.17

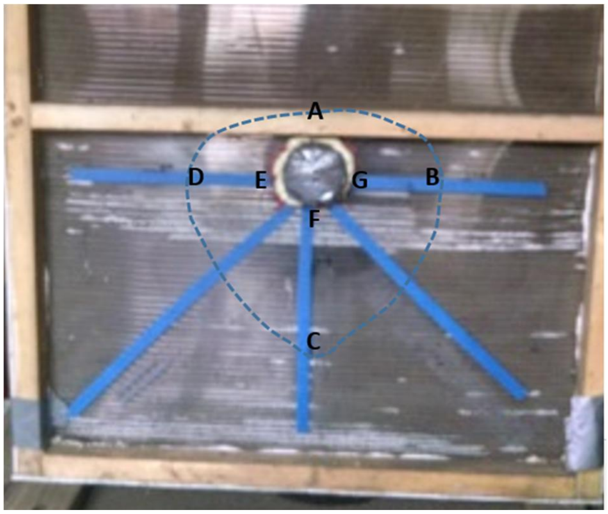


Figure 47. Dotted line represents the approximate extent of centrate movement after 48 hours.

As shown in Table 35, water moved more evenly throughout the soil space than did nitrogen—concentrations of water, after 48 hours and 2 applications of centrate, resulted in a standard deviation of only 0.02 cm^3/cm^3—only 13% of the average water concentration in each of the sampled locations. In contrast, the standard deviation of the recorded NH_4-N concentrations was 283 mg NH_4-N/kg soil—174% of the average NH_4-N concentration—showing that water tended to move more evenly through the soil, compared to NH_4-N which was more variable and remained closer to the pipe.

Summary of 2014 Results:

- Grain yield remained higher in SI treatment plots than Non-SI despite 52% more precipitation
- High levels of precipitation and less time for roots within the SI N delivery matrix resulted in more similar NUptE between SI and Non-SI U treatments
- Applying nitrogen—both through SI and Non-SI—successfully enhanced nitrogen uptake, even at rates up to 2 times that which is needed by the plant
- Water moved further and more evenly away from the SI pipe than did nitrogen, indicating different mechanisms for movement (Bray, 1942) and a need for optimization of design for the system according to different parameters
- High disease pressure from continuous corn and late planting resulted in low grain yields and nitrogen uptakes for all plots compared to 2013, but the same patterns for water and nitrogen uptake were observed and/or explained by weather

CHAPTER 6: CONCLUSIONS & RECOMMENDATIONS

Summary & Conclusions

The main objective of this study was to evaluate corn grain yield and plant nitrogen uptake with AD centrate or urea through SI. Results indicated that SI was effective at enhancing grain yield by 18% during the 2014 growing season compared to Non-SI treatments ($p = 0.05$); and it was only in the 2013 growing season that SI was more effective—14%—at delivering nitrogen to the plants late in their growth cycle ($p = 0.05$). This demonstrates the variable benefits that SI can have on a system—thus aiding its benefit in a variety of climate conditions. Obstacles and challenges resulting from continuous corn, late planting, and plot assignments depressed the benefit of enhanced nitrogen uptake in both growing seasons. Many models for N application in agriculture are limited in their capacity to deliver nitrogen late in the growing season, when the plant needs it most. Delivering centrate as an effective nitrogen source in all seasons and as a water source, even in wet seasons, provides economic and environmental benefits to both farmers and WTPs.

Water and nitrogen move by very different mechanisms in the soil—demonstrated by their variable effect on plant growth in each of the growing seasons and the only 13% variation observed with water movement within the soil profile box and 174% variation observed with NH_4-N movement within the soil profile box. It is for this reason that optimization of an SI system that effectively provides centrate as a water and as a nitrogen source to corn plants must be done with this in consideration.

Future Work

Comprehensive knowledge of all of the benefits of the system in this study is needed to better assess the allocation of costs and benefits in a farmer-WTP partnership.

Future work may concern itself with the following investigations:

- Compare the following parameters in a long term study between a fall-applied anhydrous ammonia continuous corn system and a V8-applied centrate-SI continuous corn system
    - Soil bulk density from increased tractor passes with anhydrous ammonia
    - Ground water nitrate-nitrogen contamination
    - Per hectare contribution of the GHG nitrous oxide
    - Soil microbiota
- A cost analysis for increasing nitrogen uptake and enhancing nitrogen treatment efficiency through closer SI pipe spacing

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APPENDIX

Table 36. Relationship between grain yield and precipitation from May 1 to September 30th from 2005 to 2014 in Champaign County

Year	Grain Yield (kg/ha)	Precipitation (cm)
2014	11475	66.8
2013	8909	37.0
2012	5772	43.9
2011	8697	38.6
2010	8984	51.6
20092	10070	58.0
2008	9328	74.4
2007	9964	36.3
2006	9540	42.9
2005	8692	39.6

Table 37. "Non-Application Days" as defined by "Illinois Design Standards for the Land Application of Treated Wastewater"

- When the soil is frozen, including sub-soil frost
- When there is an ice or snow cover on the ground
- When the soil temperature at 10 cm is below 4.4°C
- When the mean air temperature is below 1.7°C
- When standing water is present
- When the groundwater table is within 1.2 m
- During days when precipitation exceeds 0.3 cm
- During agricultural and horticultural management operations

Table 38. Centrate characteristics during the growth period

Date	Source	NH_3-N (mg/L)	Total N-N (mg/L)	TSS (mg/L)
08/21/13	Centrate		*1100*	**488**
08/2013	Centrate	**937**		**456**
09/5/13	Centrate		*1100*	
09/2013	Centrate	**978**		**214**
08/21/14, Trip 1	Centrate	*300*		
08/21/14, Trip 2	Centrate	*660*		
08/21/14, Trip 3	Centrate	*680*		
08/28/14, Trip 1	Centrate + GBE	*330*		
08/28/14, Trip 2	Centrate	*710*		
08/28/14, Trip 3	Centrate + GBE	*500*		
08/2014	Centrate	*952*		
09/12/14, Trip 1	Centrate + GBE	*330*		
09/12/14, Trip 2	Centrate + GBE	*400*		
09/12/14, Trip 3	Centrate + GBE	*210*		
09/2014	Centrate	***924***		**272**

Bolded values indicate measurements taken by UCSD NE-WTP

Italicized values indicate measurements taken by project investigators

All TSS values represent measurements taken by UCSD NE-WTP

GBE: Gravity belt effluent

Table 39. Estimations of N uptake with respect to a 113 d RM hybrid in non-limiting N conditions (Bender, Haegele et al., 2012)

Nitrogen uptake stage	**kg N assimilated/ha**		**MGDD_c**	**kg N assimilated/MGDD_c**
	Start	End		
Early vegetative	0	56	463	0.12
Late vegetative	56	186	269	0.48
Reproductive	186	286	674	0.15

Table 40. 2013 Fertilizer Applications

	SI Field										
2013	SICW Plot 2	No N Plot 3	SIUW Plot 4	No N Plot 5	SIUW Plot 6	No N Plot 7	Non-SI U Plot 8	No N Plot 9	SICW Plot 10	No N Plot 11	Non-SI U Plot 12
8/7	55 kg N/ha (centrate-SI)	-	50 kg N/ha (urea-SI)	-	50 kg N/ha (urea-SI)	-	55 kg N/ha (urea-topical)	-	70 kg N/ha (centrate-SI)	-	55 kg N/ha (urea-topical)
8/15	55 kg N/ha (centrate-SI)	-	50 kg N/ha (urea-SI)	-	50 kg N/ha (urea-SI)	-	55 kg N/ha (urea-topical)	-	70 kg N/ha (centrate-SI)	-	55 kg N/ha (urea-topical)
8/20	55 kg N/ha (centrate-SI)	-	50 kg N/ha (urea-SI)	-	50 kg N/ha (urea-SI)	-	55 kg N/ha (urea-topical)	-	70 kg N/ha (centrate-SI)	-	55 kg N/ha (urea-topical)
8/28	55 kg N/ha (centrate-SI)	-	50 kg N/ha (urea-SI)	-	50 kg N/ha (urea-SI)	-	-	-	70 kg N/ha (centrate-SI)	-	-
8/29	-	-	-	-	-	-	55 kg N/ha (urea-topical)	-	20 kg N/ha (urea-topical*)	-	55 kg N/ha (urea-topical)
9/5	55 kg N/ha (centrate-SI)	-	50 kg N/ha (urea-SI)	-	50 kg N/ha (urea-SI)	-	55 kg N/ha (urea-topical)	-	70 kg N/ha (centrate-SI)	-	55 kg N/ha (urea-topical)
9/13	0.72 kg N/ha (water-SI)	-	0.06 kg N/ha (water-SI)	-	0.06 kg N/ha (water-SI)	-	-	-	0.9 kg N/ha (water-SI)	-	-
9/20	0.72 kg N/ha (water-SI)	-	0.06 kg N/ha (water-SI)	-	0.06 kg N/ha (water-SI)	-	-	-	0.9 kg N/ha (water-SI)	-	-

Table 40 continued

10/3	0.72 kg N/ha (water-SI)	-	0.06 kg N/ha (water-SI)	-	0.06 kg N/ha (water-SI)	-	-	-	0.9 kg N/ha (water-SI)	-	-
10/10	0.72 kg N/ha	-	0.06 kg N/ha (water-SI)	-	0.06 kg N/ha (water-SI)	-	-	-	0.9 kg N/ha (water-SI)	-	-
Total	300 kg N/ha	-	250 kg N/ha	-	250 kg N/ha	-	275 kg N/ha	-	400 kg N/ha	-	275 kg N/ha

Table 41. 2014 Fertilizer Applications

	SI Field									Non-SI Field						
2014	SICW Plot 2 Low N	No N Plot 3	SIUW Plot 4 Low N	No N Plot 5	SIUW Plot 6 High N	No N Plot 7	SIW Plot 8	No N Plot 9	SICW Plot 10 High N	NonSI Plot 2 Low N	NonSI Plot 3 No N	NonSI Plot 4 Low N	NonSI Plot 5 No N	NonSI Plot 6 High N	NonSI Plot 7 No N	NonSI Plot 8 High N
6/11	49 kg N/ha (urea-topical)	-	49 kg N/ha (urea-topical)	-	49 kg N/ha (urea-topical)	-	49 kg N/ha (urea-topical)	-	49 kg N/ha (urea-topical)	-	-	-	-	-	-	-
7/17	70. kg N/ha, 78 kg P/ha (DAP-topical)															
8/1	0.5 kg N/ha (water-SI)	-	0.4 kg N/ha (water-SI)	-	0.4 kg N/ha (water-SI)	-	0.5 kg N/ha (water-SI)	-	(No water applied)	-	-	-	-	-	-	-

Table 41 continued

8/8	33 kg N/ha, 37 kg P/ha (DAP-topical + shallow tillage)															
8/14	0.36 kg N/ha (water-SI)	-	0.18 kg N/ha (water-SI)	-	0.18 kg N/ha (water-SI)	-	0.36 kg N/ha (water-SI)	-	0.36 kg N/ha (water-SI)	-	-	-	-	-	-	-
8/18		33 kg N/ha, 37 kg P/ha (DAP-topical + shallow tillage)														
8/20	100 kg N/ha (centrate-SI)	-	46 kg N/ha (urea-SI)	-	92 kg N/ha (urea-SI)	-	0.72 kg N/ha (water-SI)	-	150 kg N/ha (water-SI)	-	-	-	-	-	-	-
8/27									-	190 kg N/ha (urea-topical)	-	190 kg N/ha (urea-topical)	-	190 kg N/ha (urea-topical)	-	190 kg N/ha (urea-topical)
8/28	50 kg N/ha (centrate--SI)	-	46 kg N/ha (urea-SI)	-	92 kg N/ha (urea-SI)	-	0.72 kg N/ha (water-SI)	-	180 kg N/ha (centrate-SI)	-	-	-	-	-		-
9/4	-	-	-	-	-	-	-	-	-	-	-	-	-	190 kg N/ha (urea-topical)	-	190 kg N/ha (urea-topical)
9/12	50 kg N/ha (centrate-SI)	-	46 kg N/ha (urea-SI)	-	92 kg N/ha (urea-SI)	-	0.72 kg N/ha (water-SI)	-	100 kg N/ha (centrate-SI)	-	-	-	-	-	-	-

Table 41 continued

10/7	0.18 kg N/ha (water-SI)	-	93 kg N/ha (urea-SI)	-	150 kg N/ha (urea-SI)	-	0.18 kg N/ha (water-SI)	-	0.18 kg N/ha (water-SI)	-	-	-	-	-	-	-
10/13	-	-	-	-	-	-	-	-	-	14 kg N/ha (urea-topical)	-	14 kg N/ha (urea-topical)	-	130 kg N/ha (urea-topical)	-	130 kg N/ha (urea-topical)
Total	390 kg N/ha, 150 kg P/ha	140 kg N/ha, 150 kg P/ha	420 kg N/ha, 150 kg P/ha	140 kg N/ha, 150 kg P/ha	610 kg N/ha, 150 kg P/ha	140 kg N/ha, 150 kg P/ha	190 kg N/ha, 150 kg P/ha	140 kg N/ha, 150 kg P/ha	620 kg N/ha, 150 kg P/ha	340 kg N/ha, 150 kg P/ha	140 kg N/ha, 150 kg P/ha	340 kg N/ha, 150 kg P/ha	140 kg N/ha, 150 kg P/ha	650 kg N/ha, 150 kg P/ha	140 kg N/ha, 150 kg P/ha	650 kg N/ha, 150 kg P/ha

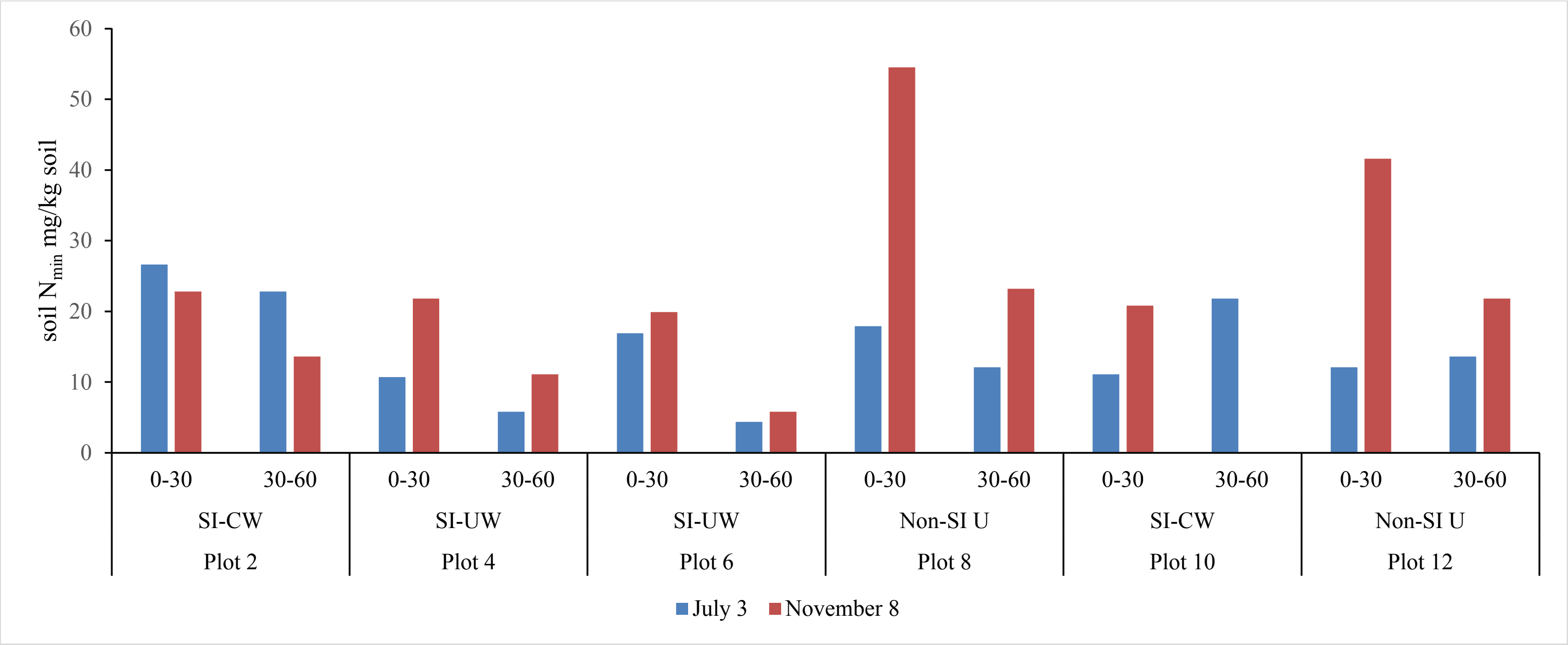

Figure 48. Changes in soil mineral N per treatment plot in 2013

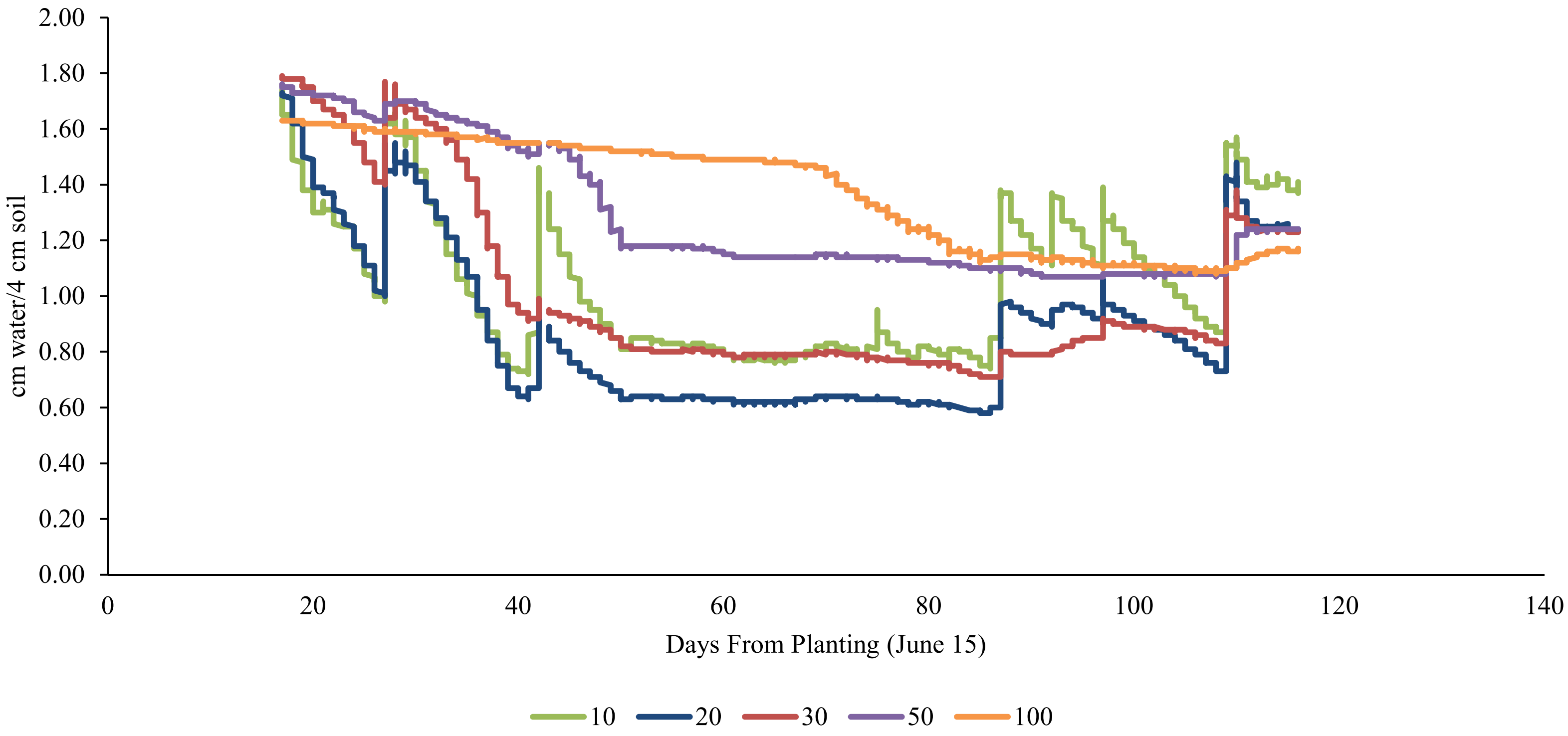

Figure 49. Soil moisture (cm water/4 cm soil) in 2014 (Bender, unpublished data, 2014. Urbana, IL: University of Illinois)

Table 42. Kilograms of heavy metals applied per year for each wastewater product (Source: Anderson, 2010; Chipasa, 2001; Silva et al., 2007)

Heavy Metal	Biosolids (54,300 kg/ha, < 2,720 kg N/ha)	Centrate (400 kg NH_4-N/ha, 150 mg/L TSS)
As	0.39	4.4E-4
Cd	0.40	4.4E-4
Cr	12	1.3E-2
Cu	23	2.5E-2
Hg	0.19	2.1E-4
Ni	2.0	2.2E-3
Pb	15	1.6E-2
Zn	78	8.6E-2

Table 43. Hectares irrigated per year with centrate (Based upon 190,000 L/d with 900 mg NH_4-N/L centrate)

cm-ha wastewater (400 kg NH_4-N/ha)	Ha covered
4.4	6.9