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Improving the Efficiency of Fall Applied N with Cover Crops

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WITH COVER CROPS

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Nitrate loss studies in Midwestern tile-drained fields have found that fall applied nitrogen (N) resulted in elevated nitrate concentrations in tile water during both the corn and soybean year of a 2 year rotation. The effectiveness of cover crops to reduce nitrate leaching when N is spring applied has been well demonstrated, however there is a dearth of knowledge on the ability of cover crops to reduce nitrate leaching in a system where N is fall applied. Thus, the objectives of this research were to (i) investigate the efficacy of winter cover crops to reduce nitrate leaching from fall applied nitrogen and (ii) nvestigate the impact of cover crops on N mineralization in the spring before planting main crops. The experimental site was located at the Illinois State University Research and Teaching Farm in Lexington, IL. All treatments received fall nitrogen at a rate of 200 kg ha^{-1} into standing cereal rye, tillage radish and control (no cover crop). Cover crops were sampled and analyzed for total nitrogen to calculate N-uptake. Soil samples were collected during the fall and spring months and analyzed for nitrate and ammonium. Despite variable weather conditions, both cover crop treatments demonstrated the potential to reduce nitrate leaching compared to a no cover crop control. The tillage

radish treatment resulted in consistently greater soil inorganic N compared to other treatment immediately before planting. In contrast, cereal rye residue slowly decomposed over time and resulted in a slower rate of mineralization. Therefore, both cover crop species increased the efficiency of fall applied N by reducing nitrate leaching and increasing inorganic N at the soil surface.

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NITROGEN WITH COVER CROPS

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CHAPTER I

INTRODUCTION AND BACKGROUND

Nitrogen loss from agriculture fields is a major environmental, health, and economic concern. Nitrate-nitrogen is the form of mineral nitrogen most susceptible to loss because it is repelled by negatively charge clay minerals. This loss of nitrate from agriculture fields has been linked to the development hypoxic zones and drinking water contamination. Hypoxic zones are areas of low dissolved oxygen that occur naturally across the world in deep oceans and lakes (Kamykowski and Zentara, 1990). An increase in hypoxic zones near coasts has been linked to increased human activity (Diaz and Rosenberg, 1995). For example, the hypoxic zone in the Gulf of Mexico has been linked nitrogen loading in the Mississippi River Basin (Rabalais et al., 2002a).

Little progress has been made in decreasing nitrate flux in the Mississippi River Basin (MRB) since 1980 (Sprague et al., 2011). Agriculture fields are a major source of nitrogen to the MRB. David et al. (2010) estimated that 76% of nitrogen loading into the Mississippi River can be explained by fertilizer application timing and precipitation. Agriculture fields in Minnesota, Iowa, Illinois, Indiana, and Ohio contribute the greatest estimated nitrate flux into the Mississippi River (David et al., 2010). Two factors that increase nitrate leaching are tile drainage and nitrogen fertilizer timing.

Nitrate leaching is the greatest during wet fall and spring months when the absence of nitrogen uptake from a main crop leaves nitrate susceptible to leaching (Gilliam and Reddy, 1999; Dinnes et al., 2002; Smiciklas and Moore, 2008). Tile drainage may provide a pathway for nitrate to enter surface water via subsurface flow. As a result of this pathway, surface Best Management Practices (BMPs) ineffective at reducing nitrogen loading into nearby surface water (Lemeke et al., 2011). Fall applied nitrogen fertilizer increases nitrate leaching compared to fertilizer applied in the spring (Randall, 2005). Greater loss of fall applied nitrogen likely contributes to decreased yield when compared to spring fertilization (Welch et al., 1970; Jokela , 1992; Scharf et al., 2002; Randall et al., 2003). However many producers choose to apply nitrogen in the fall (Smiciklas et al., 2008) because of spring time constraints, better field conditions, and lower fertilizer costs.

Cover crops grown during the fall, winter and early spring could possibly reduce loss of fall applied nitrogen by capturing N fertilizer in the fall and storing it as plant biomass. The cover crops either die back naturally, during the winter or are chemically terminated in the spring. As the cover crops residue mineralizes they release nitrogen to the main crop in the following spring. Studies in Maryland, Georgia and Mississippi have shown that cover crops can reducing leaching of residual spring applied N (Shipley et al., 1992; McCracken et al., 1994; Dean and Weil, 2009). Adeli et al. (2011) observed that cover crops could effectively reduce leaching of fall applied N in southern climates. There is a need to investigate the ability cover crops to reduce NO_3 leaching from fall applied N in tile-drained Midwest soils.

This research was conducted from August 2011 to August 2013 at the Illinois State University Farm in Lexington, IL. The study investigated the ability of cereal rye, crimson clover and tillage radish to improve the efficiency of fall applied nitrogen. Cereal rye was chosen because of popularity, aggressive fall and spring growth and its ability to reduce nitrate leaching. Crimson clover was included because it is a legume and has the potential to amend nitrogen applications by fixing atmospheric N. However, it is not understood how fall N application will impact clover's ability to fix nitrogen. Tillage radish was selected because it is a cover crop of increasing popularity due to its aggressive fall growth and that it winter kills. The second aspect of this project was to investigate when fall applied N is released to the following main crop. To evaluate N uptake of cover crops samples were collected in the winter before radish was winter killed and spring before rye and clover were chemically terminated. To investigate nitrate leaching soil samples were collected to a depth of 80cm when cover crops were first planted and additional soil sampling occurred in the spring after cover crops were chemically terminated. Soil N mineralization was examined by sampling 0-20cm depth every two weeks from March to May.

Research hypotheses

1. Cereal Rye, Crimson Clover, and Tillage Radish will have the capacity to take up fall applied N. Tillage radish will have the greater N uptake (kg N ha^{-1}) then cereal rye or crimson clover.
2. All cover crop treatments will have smaller soil nitrate concentrations at lower depths then in the no-cover control.

3. All cover crop treatments will have greater soil nitrate concentrations at upper depths than in the no-cover control.
4. Radish will have a greater soil mineralization rate then cereal rye and crimson clover. All cover crop treatments will have a greater mineralization rate the no-cover control.

Research Objectives

1. Quantify the N uptake of Cereal Rye, Crimson Clover and Tillage Radish to capture fall applied nitrogen.
2. Measure Soil nitrate concentrations at 0-5cm, 5-20cm, 20-50cm and 50-80cm depths under each cover crop treatment and the no-cover control.
3. Measure soil nitrate mineralization rate during the period from cover crop termination to corn planting.

CHAPTER II

LITERATURE REVIEW

Development of Hypoxia in the Gulf of Mexico

Eutrophication is the result of increased nutrient input, specifically nitrogen and phosphorous, and is a natural process in fresh water systems. Excessive nutrient inputs can lead to accelerated eutrophication and development of hypoxia. Hypoxia is an area of water with low oxygen concentrations. Hypoxic environments are common around the world and throughout history have often been found in deep lakes and lower ocean depths (Kamykowski et al., 1990). These zones develop naturally as a water column stratifies into multiple layers. At the surface, turbulence and diffusion mix atmospheric oxygen into the water column. Temperature and salinity changes cause the water column to stratify at lower depths. This stratification prevents diffusion of oxygen and creates hypoxic zones. However, the presence of hypoxic zones in shallow coastal waters, and estuaries has increased in recent decades due to eutrophication of tributary waters (Diaz, 1995). This growth is correlated with population growth, increased agriculture, and human activity (Diaz and Rosenberg, 1995; Nixon, 1995; Vitousek et al., 1997; Caraco and Cole, 1999). An example of this is the hypoxic zone off the Gulf of Mexico. Rabalais et al. (2002b) observed that the Gulf of Mexico hypoxic zone is the second largest hypoxic zone in the world. The popular press calls this hypoxic zone the "Dead

Zone" which refers to the inability to catch bottom dwelling fish, shrimp and crabs (Renaud, 1986). It is not an area without life; upper depths support swimming organisms and lower depths support many microbes that are adapted to low-oxygen, hypoxic conditions. The presence of the Gulf of Mexico hypoxic zone has led to reduced biodiversity and changes in ecosystem structure and functioning (Rabalais, 2001).

The Mississippi River is a primary source of nitrogen flux into the Gulf of Mexico (Tuner, 1994; Turner and Rabalais, 2006; Committee on Environment, Natural Resources and Sustainability, 2010). Nitrogen losses from agriculture are a major cause of hypoxia in the Gulf and eutrophication of surface waters in the Mississippi River Basin. Nitrogen loading from the Mississippi River alone is four times greater than pre-industrial levels (Howarth et al., 1996). Watersheds with extensive agriculture activity are the main contributors of N flux to the Mississippi (Rabalais, 2002; David, 2010). On average 1.6 million metric tons of N flows from the Mississippi River into the Gulf of Mexico each year and agriculture sources account for 45% of that N flux (Rabalais, 2002a). Within the Mississippi River Basin, the Midwest is estimated to be the greatest contributor of nitrate flux into the Gulf (David et al., 2010).

Nitrogen Fertilizer Loss from Agriculture Fields

Nitrogen fertilizer is an important component to farm profitability and is closely tied to corn production in the Midwest. In general, all nitrogen fertilizer is applied in either the fall or the spring. Multiple studies have shown that spring nitrogen applications result in increased corn yield relative to fall applied N (Welch, 1970; Randall et al., 2003;

Vetsch and Randall, 2004). Welch (1970) observed that spring applied nitrogen resulted in greater yield at low fertilizer rates (57 and 134 kg N ha^{-1}) compared to fall applied N. Randall (2003) observed higher % N recovery, greater corn yield, and corn N uptake when nitrogen was spring applied vs. fall applied. Vetsch and Randall (2004) observed spring application was superior to fall because it optimized profitability regardless of other management (tillage). Observed variations in corn yield when N was fall applied could be explained by climatic difference between years. In years with wet springs, N applied in the fall is considerably more susceptible to loss then spring N. Randall and Vetsch (2005) conducted a 7 year study investigating the impact of N application timing on nitrate leaching via tile water. The researchers observed that when nitrogen was both fall and spring applied 73% nitrate loss occurred in the spring. However, fall applied nitrogen was more susceptible to loss especially in springs with above average precipitation. One year of the study (1999), had 47% greater spring precipitation than the 30 year average for the region. Nitrate leaching during the same year accounted for 48% of the total nitrate lost from fall applied N over the entire study. Researchers observed that spring application reduced nitrate leaching by 14% compared to fall. These findings agree with earlier observations by Sanchez and Blackmer (1988) that 49-64% of fall applied N was lost from the top 1.5m of the soil by methods besides plant N uptake. Despite greater N loss and decreased corn yield, in some areas of the Midwest up to 50% of nitrogen fertilizer still is fall applied. Producers likely choose to fall apply N because of time constraints around planting and delays associated with wet spring weather (Smiciklas, 2008b; Smiciklas, 2008a). Additionally, it is often economically favorable to fertilizer dealers and less expensive for producers to apply fertilizer in the fall (Randall, 2003).

Tile drainage is necessary to maximize production on about 25% of the cropland in the United States (Pavelis, 1987; Shady, 1989; Skaggs et al., 2012). However, tile-drainage has also been shown to increase nitrogen loss from fields and increase nitrate concentrations in nearby surface water (Gilliam et al., 1999; Smiciklas et a;, 2008b; Smiciklas and Moore, 2008a). Keeney and Deluca (1993) reported that nitrogen fertilizer use resulted in elevated nitrate concentrations in nearby surface water. Schilling and Libra (2000) conducted a study evaluating the surface water nitrate concentration in 25 Iowa watersheds. These watersheds land use ranged from 24 to 87% row crop agriculture and were commonly tile-drained. Percentage of land with tile drainage was not reported. Researchers observed a linear relationship between row-crop, tile-drained agriculture and nitrate concentrations in surface water. Dinnes et al. (2002) concluded that tile-drainage acts as a direct pipeline for nitrate to flow directly to surface water. Many current surface best management practices are in-effective at reducing nitrate in surface water (Lemke et al., 2011). Researchers observed that in an agriculture dominated watershed (>90% row crop land use, and extensive tile-drainage) increased use of grassed waterways, stream buffers, and strip-tillage had no impact on nitrate concentrations in surface water. Lemeke et al.(2011) concluded that tile- drainage has considerably altered the hydrology of the region and provided a path of nitrate to leave agriculture fields in flow directly into surface water.

Producers can adopt best management practices to reduce N loss from fields. These practices include: improved N application timing and rate, adoption of new N application equipment, and nitrification inhibitors. Changing N applications from fall to spring can considerably reduce N loss (Sanchez and Blackmer, 1988; Randall and

Vetsch, 2005). Uniform N application rates are inefficient across a single field or multiple fields because of natural soil N variability (Power et al., 2000). Conventionally, N rate recommendations are made at the state or regional scale. By making recommendation at the field scale producers can avoid over application of nitrogen and reduce N loss (Dinnes et al., 2002). Adoption of new application equipment by producers can reduce N loss. For example, the localized compaction and doming (LCD) applicator can be used to reduce N loss from leaching, volatilization, and runoff (Ressler et al., 1997). The LCD applicator creates a compacted layer of soil above the injection zone of liquid N fertilizer. The compacted zone reduces infiltration and nitrate leaching locally. Nitrification inhibitors reduce N leaching by preventing *Nitrosomonas* bacteria from converting ammonium to nitrate. Randall and Vetsch (2005) and Stehouwer and Johnson (1990) observed that the use of inhibitors reduced nitrate leaching and increased yield from fall applied N.

Other forms of N management practices have focused on reducing N losses via tile water interception. Kovacic et al. (2006) observed that created wetlands can effectively capture up to 48% of N leachate in tile-water and release it into the atmosphere by denitrification. However, wetlands may not be effective at reducing nitrate leaching during months with high precipitation. Xue et al. (1999) concluded that months with high precipitation resulted in smaller N residence time and only a small percentage of N being denitrified by wetlands. Bioreactors use a supplemental C source to drive denitrification of N and prevent N loss to surface waters. In the laboratory, Volokita et al. (1996) demonstrated that newspapers could be used as a C source to remove N from leachate. Blowes et al. (1994) used sand, compost and bark to create bioreactors to removed N from farm drainage water. These bioreactors can be used to in the field to remove a significant amount of nitrate from tile-water (Greenan et al., 2009). However, each of these studies were only conducted over a few months. It is assumed that over several years of use bioreactor effectiveness would decrease and eventually need to be replaced. Similarly, wetlands need to be dredged periodically to maintain efficiency. Bioreactors and wetlands are point-source solutions to prevent N from entering surface water. However, they still result in N fertilizer leaving the farm which is an agronomic concern to producers. There is potential to improve the efficiency of N fertilizer with cover crops. Cover crops may be non-point source solution to N leaching, that allow N to be recycled on the farm.

Impact of Cover Crops on Nitrogen Leaching

Potential environmental and agronomic benefits have led to a renewed interest in cover cropping across the Midwest. For our purpose, cover crops are crops grown from fall to spring between main crops when fields are often bare. Modern cover crop research has demonstrated on-farm benefits to cover cropping. Drinkwater et al. (1998) observed that introducing legume cover crops into a cropping system increased soil organic C. Lotter et al. (2003) reported that in drought years, corn yield was greater in systems that included cover crops than those without. Cover crops can also control weed populations through competition, allelopathy, increasing weed seed decay and maintaining surface residues (Creamer, 1996; Lawley et al., 2010). Cover crops can also reduce the need for fumigation and pesticide use by disrupt disease and pest cycles (Honeycutt et al., 1996; Gebremedhin et al., 1998). Weil and Kremen (2007) found that increased soil quality, weed and pest control, reduced soil compaction and improved nutrient cycling give cover crops the potential to provide long-term benefits that may make them profitable to producers.

Using cover crops to manage soil nitrogen may provide an immediate benefit to farmers and be an incentive to increase cover crop adoption. Cover crops have been shown to reduce leaching of residual N in a variety of cropping systems and geographic regions. In Maryland, Dean and Weil (2009) reported that brassica and cereal rye cover crops decreased soil nitrate compared to winter weed controls. In this study brassicas and rye had similar spring growth and N uptake. Brassicas (radish) that are winter-killed, increased nitrate leaching relative to the winter weed control on sandy soils. However, radish did not increase N leaching on finer texture soils. Winter cold killed the radish cover crops, allowing mineralization to occur several weeks earlier. In the Midwest, early mineralized N from radish plants maybe more susceptible to leaching via tile-drainage.

In Georgia, McCracken et al. (1994) observed that cereal rye held nitrate leachate concentrations at nearly zero kg N L^{-1} over fall, winter and early spring. During the same time period the greatest nitrate leaching was observed under winter fallow plots. Hairy vetch (legume) reduced nitrate leaching compared to winter fallow. However, vetch was less effective at reducing nitrate leaching than rye. Using labeled N^{15} fertilizer Shipley et al. (1992) observed that 45% of N uptake in cereal rye came from residual fall N as opposed to spring applied N. Cereal rye had greater residual fall N uptake than annual ryegrass (27%), hairy vetch (10%), crimson clover (8%) and native weed cover (8%). Both McCracken et al. (1994) and Shirpley et al. (1992) concluded that aggressive fall and spring growth, an extensive rooting system and earlier spring growth resulted in superior performance of cereal rye over other cover crops. However, Dean and Weil

(2009) observed that both cereal rye and radish reduce N leaching and had similar N uptake. It is not understood if cereal rye or radish would be more effective at reducing nitrogen leaching in tile-drained soils in the Midwest.

Legumes have poor ability to recover residual fall N compared to grasses (Shirpley et al., 1992). However, it is possible to improve the performance of legumes by timing nitrogen application with legume N needs. In California, Jones et al. (1977) saw only slightly lower N recoveries between subterranean clover (45%) and bromegrass (55%) when N was applied in February. Legumes may not be efficient at preventing leaching of fall applied nitrogen since both these studies show improved N recovery only when nitrogen was spring applied. However, leguminous cover crops do have the potential to fixed atmospheric N to amend fall fertilizer applications. In Mississippi, Zablototowicz et al. (2010) observed that leguminous cover crops (Austrian winter pea and hairy vetch) could provide over 150kg N ha^{-1} to cotton. They also found that when no fertilizer was applied, legumes increased cotton lint yield compared to the control. This observation suggests that legumes have the potential to supply fixed N to fields and reduce rates of fall applied N. The ability of legumes to augment fall N applications and to reduce nitrate leaching in the Midwest needs to be investigated.

There is a lack of research that investigates the efficacy of cover crops to sequester fall applied N in the Midwest corn-belt. In the Mississippi delta, Adeli et al. (2011) reported that cereal rye reduced nitrate leachate levels from fall applied boiler liter to near zero in the winter, fall, and spring. However, slow N mineralization of cereal rye resulted in reduced cotton yield relative the control. Mineralization of rye residue was likely limited by high C/N ratio in the plant (Kuo et al., 1997). Nitrogen immobilization by cover crops has been linked to decreased yield of the main crop in multiple studies (Adeli et al., 2011, Weil and Kreman, 2006; McCracken et al., 1994; Shirpley et al., 1992). Additionally, Adeli et al. (2011) observed that this immobilization of N was likely because N release from cover crops is not synchronized with the nitrogen needs of the following cash crop. Based upon the pool of knowledge in the literature, one critical question that must be explored when using cover crops to stabilize fall applied N is, when do cover crops release the sequestered fall applied N back to the soil to the subsequent cash crop?

The inclusion of cover crops to improve the efficiency of nitrogen fertilizer in conventional row-crop agriculture is an emerging research area. There is a need to quantify the impact of different cover crop species ability to sequester and release nitrogen in the Midwest. Therefore, the objectives of this study were to: 1.) Compare different cover crops species ability to reduce nitrate leaching following fall applied nitrogen. 2.) Establish when fall applied N will be released to the soil after cover crop termination.

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CHAPTER III

IMPACT OF COVER CROPS ON NITRATE LEACHING FOLLOWING FALL N APPLICATION

Abstract

Nitrate loss studies in Midwestern tile-drained fields have found that fall applied nitrogen (N) resulted in elevated nitrate concentrations in tile water during both the corn and soybean year of a 2 year rotation. The effectiveness of cover crops to reduce nitrate leaching when N is spring applied has been well demonstrated, however there is a dearth of knowledge on the ability of cover crops to reduce nitrate leaching in a system where N is fall applied. Thus, the objective of this study was to investigate the efficacy of winter cover crops to reduce nitrate leaching from fall applied nitrogen. The experimental site was located at the Illinois State University Research and Teaching Farm in Lexington, IL. Fall nitrogen was applied at a rate of 200 kg ha^{-1} into standing cereal rye, tillage radish and control (no cover crop). Cover crops were sampled and analyzed for total nitrogen to calculate N-uptake. Soil samples were collected in the spring at 4 depths to 80cm and analyzed for nitrate. When averaged over the two years, all cover crop treatments reduced soil nitrate concentration compared to the control. In the spring of 2012, cereal rye and tillage radish reduced soil nitrate concentrations by 121.6 and 77.2 kg N ha^{-1} respectively and in 2013 cereal rye reduced total soil nitrate concentrations by

87.4 kg N ha^{-1} compared to the control. Tillage radish increased soil nitrate at 0-5 and 5-20 cm depths. However, at lower depth radish was not significantly different from the control; cereal rye, tillage radish and crimson clover all decreased nitrate leaching by reducing soil nitrate and have the potential to improve the efficiency of fall applied N.

Introduction

Nitrate loading from tiled-drained agricultural fields of the Upper Mississippi River Basin continues to be a national environmental concern. On average 1.6 million metric tons of nitrogen were estimated to flow from the Mississippi River into the Gulf of Mexico each year contributing to the development of the Gulf's hypoxic zone (Rabalais et al., 2002). The Midwest states characterized by row-crop and tile drained agriculture are estimated to be the largest contributor of N to the Mississippi River (David et al., 2010). In fact, agriculture sources alone account for 45% of that N flux (Rabalais et al., 2002). Studies have shown that tile drainage and fall applied nitrogen are common Midwest practices that can contribute to increased N leaching from agriculture fields.

Drainage is necessary to maximize production on about 25% of the cropland in the United States (Pavelis,1987; Skaggs et al., 2012). While this may increase crop yield, it has been shown to increase leaching of nitrogen fertilizer (Gilliam et al., 1999; Smiciklas and Moore, 2008; Smiciklas et al, 2008). Keeney and Deluca (1993) reported that nitrogen fertilizer use, especially on row-crop and tile-drained fields resulted in elevated nitrate concentrations in nearby surface water. Schilling and Libra (2000) observed a linear relationship between row-crop, tile-drained agriculture and nitrate concentrations in surface water. Dinnes et al. (2002) concluded that tile-drainage acts as a direct pipeline for nitrate to flow to surface water.

Studies have demonstrated that fall applied nitrogen is more susceptible to loss by leaching then spring applied nitrogen. Randall and Vetsch (2005) conducted a 7 year study investigating the impact of N application timing on nitrate leaching to tile water. The researchers observed that fall applied nitrogen was much more susceptible to loss, especially in springs with above average precipitation. One year of the study (1999), had 47% greater precipitation then the 30 year average for the region. Nitrate leaching during the same year accounted for 48% of the nitrate lost from fall applied N for the 7 years of the study. From that study Randall and Vetsch (2005) concluded that spring application of nitrogen reduced nitrate leaching by 14% compared to fall. These findings agree with earlier observations by Sanchez and Blackmer (1988) who determined that 49-64% of fall applied N was lost from the top 1.5m of the soil by methods besides plant N uptake. Additionally, greater nitrogen loss likely explains why spring nitrogen application results in increased yield relative to fall fertilization (Welch et al., 1970; Jokela, 1992; Scharf et al., 2002). Randall et al.(2003) also found that spring applied nitrogen (40% spring preplant, 60% side dress) resulted in 13% higher nitrogen recovery and 0.84 Mg Ha^{-1} greater corn yield relative to fall applied nitrogen without a nitrification inhibitor.

Despite greater nitrogen loss the potential for lower yields, studies indicates that fall N application continues to be a widely used practice by Midwest farmers. Between the years of 1993 and 2003 nitrogen management practices were surveyed within the Bloomington watershed of McLean County, IL, and the results indicated that 55% of producers in the Bloomington Watershed applied N during the fall after harvest (Smiciklas et al., 2008). Across the Midwest an average of 25% of N is fall applied; in regions were soil type and weather conditions favor fall N the number of farmers who apply N in the fall can increase to 55% (Randall and Sawyer, 2005; Smiciklas et al. , 2008). Farmers likely choose to fall apply N to avoid adverse spring weather conditions that prevent or delay N fertilization, and to take advantage of potentially lower N cost and greater availability of labor and equipment. Therefore, there is an immediate need to increase the N efficiency of the widely practiced fall N application and to educate farmers of equivalent or more lucrative N fertilizer timing alternatives.

Current surface best management practices (BMP) are ineffective at reducing nitrate from escaping to nearby surface water. Lemke et al.(2011) observed that in an agriculture dominated watershed (>90% row crop land use, and extensive tile drainage) increased use of grassed waterways, stream buffers, and strip-tillage failed to reduce nitrate concentrations in surface water. Lemke et al. (2011) concluded that tile-drainage allowed nitrate to bypass surface BMPs. Other N management practices have focused on reducing N losses via tile water interception such as constructed wetlands and inline tile bioreactors. Kovacic et al. (2006) observed that constructed wetlands can effectively reduce nitrate loading from tile drainage by up to 48% via denitrification. Similarly, bioreactors use supplemental C source to drive denitrification of N and to prevent N loss to surface waters (Greenan et al., 2009). Although, wetlands and bioreactors are effective at reducing nitrate leaching from tile-drainage, N fertilizer is still lost from agriculture fields instead of being used by cash crops.

One possible alternative N management practice available to farmers is to incorporate winter cover crops into their crop rotation. Multiple studies have shown that cover crops can reduce leaching of residual spring applied N. Using labeled ^{15}N fertilizer Shipley et al. (1992) observed that 45% of N uptake in cereal rye came from residual spring applied N fertilizer. Cereal rye had greater residual fall N uptake relative to annual ryegrass (27%), hairy vetch (10%), crimson clover (8%), and native weed cover (8%). McCracken et al. (1994) observed that cereal rye held nitrate leachate concentrations at nearly zero kg N L^{-1} over the fall, winter and early spring. Dean and Weil (2009) found that both cereal rye and tillage radish reduced soil nitrate concentrations compared to the control. There is a lack of research that investigates the impact of cover crops on fall applied N in the Midwestern corn belt. In Mississippi, Adeli et al. (2011) fall applied broiler litter immediately before planting cover crops in early October. They observed that cereal rye reduced leachate and spring soil nitrate concentrations compared to the no cover crop control. It is possible that fall applying nitrogen into a living cover crop may reduce leaching of nitrate and improve the efficiency of fall applied N in the Midwest.

Therefore the objectives of this are to (i) quantify the N uptake capacity of cereal rye, crimson clover and tillage radish to capture fall applied nitrogen (ii) understand the impact of cover crops on the distribution of spring nitrate (iii) evaluate the ability of different cover crops to reduce nitrate leaching following the fall N application. This study will allow for the assessment of the impact of different cover crop species on nitrate leaching following fall N application into a living a stand of cover crops.

Materials and Methods

The experimental site was located at the Illinois State University Teaching and Agriculture Research Farm in Lexington, IL. The dominant soils within the site were Drummer and El Paso silty clay loams. Both soils were poorly drained, contained a 0-2% slope, and required tile drainage. The cropping history of the site was continuous corn

(*Zea mays L.*) for the last 5 years to support silage production. During this study continuous corn was grown throughout the two year period. The experimental site consisted of 12 plots (2023m^2, half-acre) arranged in a complete randomized block design with 3 replications of the following 4 treatments: control (No Cover Crop), tillage radish (*Raphanus sativus L*), crimson clover (*Trifolium incarnatum L.*), and cereal rye (*Secale cereal L.*).

Following the harvest of corn silage, tillage radish, crimson clover, and cereal rye were drilled into silage residue in September. In 2011, a starter fertilizer of 50 kg ha^{-1} of N as $(NH_4)_2SO_4$ was applied in October to provide adequate cover crop nutrition and to maximize cover crop growth. In November 2011, anhydrous ammonium (150 kg ha^{-1}) was knifed into the living stand of cover crops. In November of 2012, anhydrous ammonium (200 kg ha^{-1}) was knifed into cover crops and no starter fertilizer was applied in 2012, due to elevated available N concentrations in the soil following low N absorption during a drought stricken growing season. In both years, tillage radish plants winter terminated in December and crimson clover and cereal rye were terminated in March with an application of 2,4-D and glyphosate. Spring tillage was used to incorporate cover crop residue into the soil prior to corn planting to simulate the dominant cultural practice of the region.

Plant Sampling

All plant sampling locations were randomly selected at least 1 meter from the edge of the plot in a representative location. Cover crops were sampled in the fall and spring of each year; three 0.25m^2 quadrants were collected to create a composite sample from each plot. No biomass was collected from control plots at either the fall or spring samplings. Above ground cover crop biomass was sampled and shoots were separated at the soil surface. Dry weights of the entire quadrants were measured and used for nitrogen uptake determination and analysis. Corn plants were sampled at harvest each year and total tonnage was measured from the middle 6 rows of each plot. Subsamples were taken from each plot and oven dried for 7 days to obtain percent moisture and then analyzed for N concentration. All plant samples were oven dried at 55 C^o, weighed, and ground. Ground samples were analyzed for %N using a combustion analyzer (FP523 N Analyzer, LECO St. Joseph, MI). Total N was used to establish N uptake for each cover crop treatment. Nitrogen uptake was calculated by multiplying %N by total biomass (kg ha^{-1}).

Soil Sampling

In order to determine the impact of cover crops on the efficiency of fall applied N, soil samples were collected in the fall following corn harvest and in the spring before corn planting to a depth of 80 cm and were analyzed for soil NO_3-N and NH_4-N. Through observations made while soil sampling, it was determined that the average water table was at or near 80cm. Three soil cores were randomly collected from each plot using a hydraulic probe. After collecting an intact undisturbed soil core to the 80cm depth, the core was divided at depths of 0-5cm, 5-20cm, 20-50cm, and 50-80cm. All soil samples were immediately dried for 24 hours at 105 C^o and ground through a 1mm sieve before analysis. To determine NO_3-N and NH_4-N, a 5g subsample from each depth was shaken with 50 ml of 0.01M $CaCl_2$ solution, filter with Whatman 42 filter paper, and analyzed using the ion chromatography. Following the analysis, soil nitrate N was determined for each depth by using a bulk density of 1.21g cm^{-3} for each depth.

Statistical Analysis

Statistical analysis of soil nitrate concentrations across depth, cover crop and corn N uptake, crop biomass, and corn silage tonnage was conducted using ANOVA as calculated by SAS Proc Mixed (SAS I006Estitute, Cary NC). Block effects were treated as random variables, while cover crop treatments were fixed effects. Tukey Multiple Means comparisons were used to compare treatments to each other and to the control. Due to natural soil variability and number of subsamples obtainable a P level of <0.10 was used to determine significant differences between treatments.

Results

Weather

Average air temperature for 2011 was similar compared to from the 30 year average of the Central Illinois region, with the exception of December 2011, which was 4.06 ˚C warmer than the regional average. Average monthly air temperature in 2012 was considerably warmer than the 30 year average for the region. For example; the months of January, March, May and December in 2012 were 3.61, 7.94, 3.83 and 4.67 ˚C warmer than the 30 year average, respectively. In contrast, average air temperature for 2013 was colder than the 30 year average; the months of February, March, and April of 2013 were 1.22, 4.56, and 1.78 ˚C below the regional average, respectively. Annual precipitation was greater in 2011 and 2013 than the 30 year average and was considerably below average in 2012 (Table 2). Annual precipitation in 2011 was 67.73 mm greater than the 30 year average. Annual precipitation in 2012 was 239.86 mm less than the 30 year average; the months of March, May, June, July, and November in 2012 had total precipitation 48.68, 59.27, 58.00, 66.97, and 58.42 mm below average, respectively.

Annual precipitation in 2013 was greater than the 30 year average; the months of January, April, and May 2013 had 37.68, 32.60, 57.83 mm greater precipitation compared to the 30 year average for the region, respectively.

The average air temperature for the first cover crop growing season (September 2011 – March 2012) was 2.99°C greater than the second cover crop growing season (September 2012 – March 2013). For instance, air temperature for the months of November, January, February, and March 2011 were 2.67, 1.72, 3.50 and 12.50°C warmer than the same months in 2013, respectively. The first cover crop growing season had 148.84 mm less precipitation than the second cover crop growing season. For example, September and October of 2011 and January, February and March of 2012 had 74.68, 65.28, 53.59, 25.40, and 24.89 mm less precipitation relative to the second growing season.

Cover Crop Dry Matter and Nitrogen Uptake

Tillage Radish accumulated 6,561.9 kg ha^{-1} dry matter in 2011 and absorbed 226.8 kg N ha^{-1} dry. In 2012, radish had significantly less biomass (3,707.5 kg ha^{-1}) and N uptake (131.9 kg N ha^{-1}). Radish plants did not winter kill until early January 2012. Colder air temperature in late September, October, and November of 2012 likely contributed to less radish biomass and N uptake. Cereal rye accumulated 3,906.5 kg ha^{-1} dry matter in 2011 and absorbed 188.1 kg N ha^{-1} dry. In 2012, rye had significantly greater biomass (5585.5 kg ha^{-1}) and N uptake (249.9 kg N ha^{-1}) compared to 2011. Crimson clover accumulated 1,920.0 kg ha^{-1} dry matter in 2011 and absorbed 73.2 kg N ha^{-1} dry. Due to lack of establishment clover produced a poor stand causing significantly less biomass production (124 kg ha^{-1}) and N uptake (3.8 kg N ha^{-1}) in 2012. In both years, tillage radish, cereal rye, and crimson clover had an average biomass production of 5,134.7, 4,746, and 1022 kg ha^{-1} and average N uptake of 179.4, 219.0, and 38.5 kg N ha^{-1}, respectively.

Silage Yields

Corn silage data was collected from the middle six rows of each plot at harvest each year and adjusted to 55% moisture content. Across both years fall applied nitrogen into a standing cover crop did not significantly impact corn yield or corn N uptake (Table 2). Drought conditions in summer of 2012 resulted in extremely low average corn yield across all treatments (18.8 Mg ha^{-1}) and e likely contributed to reduced N uptake of 127.3 kg N ha^{-1}. In contrast, in 2013 the silage yield was 3 times greater (51.3 Mg ha^{-1}) and N uptake (267.9 kg N ha^{-1}) was two times greater, due to more productive weather conditions.

Cover Crop Impact on Spring Soil Inorganic N

In order to investigate the impact of cover crops on spring soil NO_3-N distribution, an orthogonal contrast was performed, where all cover crop species were grouped together and then compared to the control. In the spring of 2012, cover crops significantly (P=0.02) reduced soil NO_3-N within the entire 0-80cm depth by 82.1 kg ha^{-1}. Conventional fall N application without cover crops showed a significantly higher (P= 0.004) No_3-N content of 54.1 kg ha^{-1} at the 20-50cm depth. In the spring of 2013, there were no significant differences between cover crops and control treatments. However, there was a general trend for cover crops to have less NO_3-N at the lower depths (20-50, 50-80cm) relative to the control.

More specifically in the spring of 2012 at the 0-5cm depth, the tillage radish treatment soil NO_3-N (32.87 kg ha $^{-1}$) was similar to the control (26.53 kg ha^{-1}) and was significantly (P = 0.07) greater than both the cereal rye (14.41 kg ha^{-1}) and crimson clover (8.24 kg ha $^{-1}$) treatments (Figure 2). There was no significant difference in the 5-20cm portion of the soil profile, but a similar trend was observed, where the tillage radish and control treatments resulted in the greatest soil NO_3-N followed by crimson clover and cereal rye. The conventional application of fall anhydrous without cover crops ha a significantly greater amount of NO_3-N at lower depth in the soil profile. At the 20-50cm depth the average soil NO_3-N was at least 63.5 kg ha^{-1} greater relative to all cover crop treatments that received an identical rate of fall applied N. In the lower portion of the soil profile (50-80cm) there was no significant difference in soil NO3-N among treatments.

In the spring of 2013 within the 0-5 cm depth, the tillage radish treatment resulted in significantly greater (P= 0.09) soil NO_3-N (20.12 kg ha^{-1}) relative to the control (6.33 kg ha^{-1}), but was similar to crimson clover (13.94 kg ha^{-1}) and cereal rye (10.06 kg ha^{-1}) (Figure 3). In the lower portion of the agronomic depth 5-20cm, the average soil NO_3-N (49.78 kg ha^{-1}) in tillage radish plots was again significantly greater relative the control (22.34 kg ha^{-1}, P=0.03) and the cereal rye treatments (16.49 kg ha^{-1}; P=0.07), but was not different compared to the crimson clover treatment (32.53 kg ha^{-1}). Furthermore, the crimson clover treatment resulted in significantly (P=0.05) greater soil NO_3-N at the 5-20cm depth compared to the cereal rye treatment. Data from the 20-50 cm depth exhibited a similar trend, where the tillage radish treatment resulted in significantly (P=0.06) more soil NO_3-N (64.43 kg ha^{-1}) following fall applied N relative to the cereal rye (31.74 kg ha^{-1}), but was not different from the crimson clover treatment and the control. Although there was no significant difference among treatments at the 50-80cm depth, treatments that contained cover crops reduced the concentration of NO_3-N susceptible to losses via tile drainage. Compared to the control treatment, cereal rye, crimson clover, and tillage radish reduced soil NO_3-N at the 50-80cm depth by 48%, 27%, and 14%, respectively.

In the spring of 2012, cover crops did not significantly impact the concentration or distribution of NH_4-N in the soil. On average, conventional fall N application with or without a cover crop resulted in approximately 65 kg NH_4-N ha^{-1} within the total 0-80cm soil sampling depth. In contrast, in the spring of 2013 fall applying N into tillage radish resulted in significantly more (120.4 kg ha^{-1}) NH_3-N compared to both the control (19.6 kg ha^{-1}, P=0.02) and cereal rye (48.4 kg ha^{-1}, P=0.06) at the 5-20 cm depth. In the spring of 2013, NH_4-N was 49%, 42% and 23% of total inorganic N found in the 0-80cm depth for cereal rye, tillage radish and control, respectively.

Discussion

Weather, Cover Crop Growth and Nitrogen Uptake

Differences in the distribution and quantity of precipitation and the average ambient air temperature during the winter of each year allowed for the examination of each cover crops ability to decrease the vulnerability of fall applied N under two extreme weather conditions. For instance, during the first cover crop growing season (September 2011 – March 2012), 65.5% (171mm) of the precipitation occurred in the months of November and December, after the fall application of anhydrous ammonia. In contrast, in the second year, 71.7% (194mm) of the precipitation occurred in January, February, and March of 2013, following the fall application of N. Furthermore, there was a distinct difference in the air temperature between years, where the air temperature was on average warmer in the first growing season, relative to the second cover crop growing season. The aforementioned weather conditions affected the growth of each cover crop species differently. We observed a longer tillage radish growing season (4 months of growth) in the first year, relative to the second year (3 months of growth) due to a warmer winter. Additionally, the warmer temperature and timely precipitation in the first cover crop growing season resulted in greater biomass and N uptake for the tillage radish and crimson clover relative to the second year. In contrast to tillage radish and crimson clover, the climate had less of an impact on the growth of cereal rye. Cereal rye established well in the fall of each growing season and grew rigorously in the both springs.

In the literature, cover crops have been dominantly intergraded into a spring N application system, where the cover crop is used as a tool to scavenge residual N from the previous growing season and naturally mineralized N (Ranells and Wagger, 1997 ; McCracken et al. , 1994). Cover crop N uptake in the spring system according to the literature ranged from 100-119kg ha^{-1} (Dean and Weil, 2009) and 42-78 kg ha^{-1} (Dean and Weil, 2009; Kasper et al., 2007; Strock et al., 2004) for radish and cereal rye, respectively. In our study, we used the N scavenging ability of the cover crop to stabilize fall applied N. Thus, we fall applied 200 kg ha^{-1} into a living stand of tillage radish and cereal rye. Despite dynamic weather conditions between years, both tillage radish and cereal rye N uptake ranges were 179-236 kg ha^{-1} and 189-218 kg ha^{-1}, respectively. This observation is substantial and demonstrates that both cover crop species have to ability to absorb 80-100% of the recommended or average actual rate of fall N in the Midwestern corn belt region, assuming a range of N rates applied of 200-224 kg ha^{-1} (180-200 lb A^{-1}).

Impact of Cover Crops on Spring Inorganic N

In order to quantify the impact of cover crops on fall applied N distribution within the soil profile in the spring of each year, two major areas of the soil profile were examined, the agronomic (0-20cm, the injection region of the anhydrous N) and the environmental portion of the soil profile (20-80cm; the region of the profile that is more susceptible to tile-drainage losses). In the spring of 2012, there was no significant difference between conventional fall application of N with or without a cover crop on soil NH_4-N. This could be due to warm weather that allowed for mineralization of cover crop residue to be followed closely by nitrification of NH_4-N. In contrast, in the spring of 2013, cold, wet weather may have slowed the nitrification of mineralized NH_4-N. Soil temperatures on the sampling day averaged 3.8 C° and nitrification of soil NH_4-N was reduced due to soil temperature less than 10 C° (50 F°).

Three weeks before planting in 2012 and 6 weeks before planting in 2013 at the agronomic depth, we observed greater soil nitrate for the tillage radish and control treatments in relation to cereal rye and crimson clover treatments. In the spring of 2013, corn planting was delayed until mid-may due to spring rains. However, we chose our soil sampling dates to occur about 1-2 weeks before the Illinois Agronomy Handbook's suggested planting dates for North and Central Illinois (April 16th) and Southern Illinois (April 6th) (Nafziger, 2003). A similar nitrate concentration for the tillage radish and control treatments could be attributed to the fact that the tillage radish winter kills and has a low C: N ratio relative to cereal rye and crimson clover. Based upon our observations, tillage radish winter killed in January and December of the first and second cover crop growing seasons, respectively. Thus tillage radish residue had a minimum 3 months to begin decomposing. In contrast, the cereal rye and crimson clover survived the winters and grew vigorously in the spring until terminated. Therefore, a greater percentage of scavenged fall applied N was assimilated into the plant residue and the average soil NO_3-N from both cereal rye and crimson clover was less relative to tillage radish and the control in the agronomic depth. A greater concentration of N in the agronomic depth for the tillage radish treatment could be an advantage for farmers.

Despite a warm and wet winter in 2012, fall applying N into a living stand of cover crops significantly reduced the concentration of soil NO_3-N in the environmental soil depth (20-80cm). This reduction in soil NO_3-N at the lower depth can be attributed to the ability of the cover crop to absorb fall applied N reducing its vulnerability to leaching and denitrification. At the minimum, spring NO_3-N concentrations at the 20-50 cm depth of soil in 2012 were 54% greater for the control compared to when N was fall applied into a standing cover crop. This observation is significant considering that the in some regions of the Upper Mississippi River Basin the percentage of farmers that fall apply N ranges from 25- 75% (Randal and Sawyer, 2005; Smiciklas et al., 20008; Lemeke et al., 2010; Bierman et al., 2012). Furthermore, fall N application coupled with extensive tile drainage in the region (often installed 90cm from the soil surface) results in increased potential for nitrate leaching to occur (Dinnes et al., 2002). Among the cover crop treatments, cereal rye resulted in the greatest reduction in nitrate at the 20-50cm depth, due to rigorous spring growth. Similar results were observed by Adeli et al., 2001, where they planted cereal rye and applied broiler litter in the fall which resulted in a 57%

decrease in nitrate leaching at a depth of 60cm with cover crops relative to the non-cover crop treatment.

All treatments increased in soil nitrate with depth, with the exception of tillage radish at the 50-80cm depth due to heavy precipitation in January, February and March of 2013 (194mm). Thus, in contrast to year one, tillage radish resulted in greater soil NO_3-N throughout the larger portion of the soil profile (0-50 cm depth), which is likely due to an early winter kill date that allowed for more time for residue decomposition and nitrification. In the second cover crop growing season, we observed twice as much precipitation from January t0 March 2013, relative to 2012 which facilitated spring nitrate leaching in the tillage radish treatment. This vulnerability of tillage radish scavenged N was also observed in a Maryland study that associated radish decomposition time to increased NO_3-N in soil water at lower depths on course textured soils (Dean and Weil, 2009). The vulnerability of radish NO_3-N to leaching in the spring could be managed by planting radish before corn, which is seeded earlier than soybeans and by making attempts to plant tillage radish with a winter hardy cover crop that has the potential to absorb the portion NO_3-N nitrified from the tillage radish.

To give context give context to our findings, we averaged the data across years and within treatments, which allowed us to compare the percentage of inorganic N that existed within the agronomic depths relative to the amount of N applied in the fall. The control resulted in the greatest percent of nitrate (105%) followed by tillage radish (95%), crimson clover (68%), and cereal rye (59%). Fall application of N with and without tillage radish resulted in nearly the same amount of soil nitrate in the spring. However, fall application without cover crops resulted in only 28% of soil nitrate at the agronomic depth and the majority (72%) of soil nitrate leaching to the environmental depth (20-80cm), where it is more susceptible to loss via tile drainage. In contrast, fall N application into tillage radish resulted in an average of nearly half (45%) of the soil nitrate at the agronomic depth (0-20cm) were it is less susceptible to tile-loss and more available to the following cash crop.   Additionally, in tillage radish plots a 2 year average of 56% of total inorganic N was found in the agronomic depths of the soil profile and the control treatment resulted in only 32% of total inorganic N at the agronomic depth. Additionally, at the point of this soil sampling a portion absorbed N in tillage radish residue has yet to be mineralized. This observation is important because inorganic N at the agronomic depth in tillage radish plots has the potential to increase as cover crop residue mineralizes. However, this is not true in control plots where there is no cover crop residue and therefore less potential for inorganic N to increase. When comparing cereal rye to the control we observed less soil NO_3-N then the control plots and a similar concentration of NH_4-N. However, for cereal rye we know that little decomposition had taken place due to visual observations. This indicates that the majority of the cereal rye absorbed N has yet to be released to the soil.   Therefore, a few weeks before planting there is an average of 219kg N ha^{-1} (110% of what was fall applied) that remains in cereal rye biomass that will be slowly released as the cover crop decomposes in the following summer.

Cover crops impacted the distribution of spring inorganic N following fall application by increasing NO_3-N at the soil surface and decreasing NO_3-N leaching to lower depths. Despite this, there was no significant difference in silage yield in either year.   It is likely that stress from drought conditions in the summer of 2012 limited our ability to detect any impact cover crop might have had on corn yield and N uptake. No corn silage yield response in the second growing season could be attributed to elevated N concentrations in the soil due to high residual N after the drought and the full rate of N applied in the following fall. As a result, any yield response from improved N management with cover crops was not detectable.

Conclusion

In both years, all cover crops reduced the amount of N leaching and increased the distribution of NO_3-N at the soil surface. Each year cold winter weather terminated the tillage radish at least 3 months before cereal rye and crimson clover were terminated. As the result of decomposition and nitrification, tillage radish had equal or greater soil nitrate at the agronomic depth compared to the control, 3-6 weeks before planting. However, inorganic N released from tillage radish residue was potentially susceptible to loss in the spring. In contrast, cereal rye and crimson clover had less time to decompose and nitrified N was less susceptible to loss due to spring rains.

This study has demonstrated that cover crop species influenced the availability of inorganic N in the spring following fall applied N. For example, winter-kill cover crops such as tillage radish have the greatest potential to increase the availability of fall applied N immediately before cash crops are planted. However, over-wintering cover crops with high C/N ratios that decompose slowly can better protect N from loss due to spring leaching. Additionally, there is the potential for these cover crops to slowly release N during the cash crop growing season. There is little research investigating the return of fall applied N from cover crop residue to the soil. Therefore, research is needed that correlates the timing of N release with the growth stages of cash crops such as, corn and soybeans. Additionally, our data suggests that farmers might benefit from rotating cover crops along with the rotation of their cash crops. For example a rotation of: *tillage radish– corn – cereal rye – soybeans* rotation should be considered. Planting tillage radish before corn gives the potential for a farmer to increase plant available N during the early growth of corn and decrease nitrate leaching. Planting an aggressive high C/N scavenger, such as cereal rye, after corn and before soybeans a farmer could prevent a significant amount of residual N from leaving the field and count on N to be slowly mineralized for the subsequent soybean and corn use.

Despite weather extremes, the data demonstrated that fall applying N into a living stand of cover crops reduced NO_3-N leaching, stabilized a greater percentage of fall applied N in the agronomic depth, and improved the efficiency of fall applied nitrogen.

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CHAPTER IV

IN FIELD MEASUREMENT OF NITROGEN MINERALIZATION FOLLOWING FALL N APPLICATION

Abstract

The ability of cover crops to scavenge nitrogen from the soil during winter months has been thoroughly investigated, however little is known about how cover crops impact soil mineralization in the spring before the planting of cash crops. Therefore, the objective of this study is to examine the impact of cover crop species on the release of fall nitrogen (N) to the spring cash crop following chemical termination. The experimental site was located at the Illinois State University Research and Teaching Farm in Lexington, IL. Fall nitrogen was applied at a rate of 200 kg ha^{-1} into living cereal rye, tillage radish and control (no cover crop). Cover crops were sampled and analyzed for total N to calculate N uptake. After chemical termination, soil samples were collected weekly and were analyzed for inorganic N (NO_3-N and NH_4-N) to investigate mineralization over time. Cereal rye soil inorganic N concentrations were similar to that of the control in both the spring of 2012 and 2013. Fall N application into tillage radish resulted in an average 91% of the fall N application rate as inorganic N at the soil surface immediately before corn planting. Cereal rye and control treatments resulted in 57% and 66% of the fall application rate as inorganic N at the soil surface, respectively.

However, for both cover crop treatments a significant portion of absorbed N that remained in the organic form yet to be mineralized before corn planting. The inclusion of cover crops into conventional cropping systems stabilizes N at the soil surface and has the potential to improve the efficiency of fall applied N.

Introduction

Nitrogen (N) is an essential element for crop growth and production in row-cropping systems. Many studies have compared fall and spring N applications and found that spring N often resulted in greater yield (Welch et al. , 1970; Jokela, 1992; Scharf et al., 2002). For example, in Minnesota found that spring applications (40% preplant, 60% sidedress) increased corn N recovery by 13% and yield by 14 kg ha^{-1} relative to fall applied N without a nitrification inhibitor (Randall et al., 2003). However, other considerations such as avoiding adverse spring weather and N fertilizer prices often outweigh the benefit of spring application when farmers make N management decisions. Across the Midwest, an estimated 25% of N is applied in the fall (Randall and Sawyer, 2006). In areas where soil texture and climate are favorable, fall N application can increase dramatically. For example, a survey of Minnesota farmers found that an average of 32.5% of corn acres received their main N application in the fall. Furthermore, in regions of Minnesota with finer textured soils that are more suitable to fall application, as much as 46.5% of famers reported applying the majority of their N in the fall (Bierman et al., 2011). A second study, found that over a ten year period an average of 55% of farmers in Central Illinois applied N in the fall (Smiciklas et al., 2008). Additionally, an Illinois watershed survey conducted in 2000 and 2003 in the Mackinaw River watershed (a tributary to the Illinois River) found that an average of 75% of farmers applied the majority of their N in the fall (Lemke et al., 2010). The literature demonstrates that many farmers across the Midwest are choosing to fall apply nitrogen. Despite research demonstrating that fall N is more vulnerable to loss and less corn yield (Randall and Vetsch, 2005).

Nitrate leaching from both fall and spring N application is a leading cause of N loading to surface water and the development of the Gulf of Mexico Hypoxic Zone (David et al., 2010; Rabalais et al., 2002). The timing of N application can have a significant impact on N leaching and loss from agriculture fields. For example, a study conducted over 7 years investigated the impact of N application timing on NO_3-N leaching via tile water (Randall and Vetsch, 2005). The researchers observed that fall applied nitrogen was much more susceptible to loss, especially in springs with above average precipitation. Over the entire study, fall application resulted in an average of 14% greater N leaching than spring application. However, in a single year of the study (1999), which had 47% greater precipitation then the 30 year average for the region, nitrate leaching accounted for 48% of all the nitrate lost from fall applied N over the entire study. The risk of N leaching is greatest from fall application because it has a longer time to leach between application and corn uptake. Therefor there is need to identify adaptive management practices that will improve the efficacy of fall applied N.

Cover crops are one example of an adaptive management practice that has the potential to improve the efficiency of fall applied N. Commonly, cover crops are used in spring N application systems to scavenge N between cash crop growing seasons. Nitrogen taken up by cover crops is prevented from leaching, stored within the structure of the plant and released for use by a following cash crop. Cover crops have been shown to reduce nitrate leaching when N is applied in spring in a variety of regions: Maryland (Dean and Weil, 2009), Georgia (McCracken et al., 1994), and Iowa (Kaspar et al., 2007). However, there is a lack of research that investigates the use of cover crops to improve the efficiency of fall applied N and that demonstrates the impact of cover crop species on the mineralization of soil N in the spring. In Mississippi, Adeli et al. (2011) fall applied broiler litter immediately before planting cover crops in early October and observed that cereal rye reduced leachate and spring soil nitrate concentrations compared to no cover crop control. However, slow N mineralization of cereal rye resulted in reduced cotton yield relative to the control. Mineralization of rye residue was likely limited by high C/N ratio in the plant (Kuo et al., 1997). In multiple studies spring nitrogen immobilization by cover crops has been linked to less available N for cash crops (Adeli et al., 2011, Weil and Kreman, 2006; McCracken et al., 1994; Shirpley et al., 1992). In order to improve the efficiency of fall N applications, cover crop N uptake must be followed by N release to the soil for the use by cash crops. Therefore, the objective of this study is to examine the impact of cover crop species on the release of fall N to the spring cash crop following chemical termination.

Materials and Methods

The experimental site was located at the Illinois State University Teaching and Agriculture Research Farm in Lexington, IL. The dominant soils within the site were Drummer and El paso silty clay loams. Both soils were poorly drained, contained a 0-2% slope, and required tile drainage. The cropping history of the site was continuous corn (Zea mays L.) for the last 5 years to support silage production. During the current experiment the continuous corn silage rotation was maintained. The experimental site consisted of 9 plots (2023m^2, half-acre) arranged in a complete randomized block design with 3 replications 3 treatments: control (no cover crop), tillage radish (Raphanus sativus L.), and cereal rye (Secale cereal L.).

In 2011, a starter fertilizer of 50 kg ha^{-1} of N as $(NH_4)_2SO_4$ was applied in October to provide adequate cover crop nutrition and to maximize cover crop growth. November 2011, anhydrous ammonium (150 kg ha^{-1}) was knifed into the living stand of cover crops. In November of 2012, anhydrous ammonium (200 kg ha^{-1}) was knifed into cover crops and no starter fertilizer was applied in 2012, due to elevated available N concentrations in the soil following low N absorption during the previous drought stricken growing season. In both years, tillage radish plants winter terminated by early January and cereal rye plants were terminated in March with an application of glyphosate. Spring tillage was used to incorporate cover crop residue into the soil prior to corn planting to simulate the dominant cultural practice of the region.

Plant Sampling

All plant sampling locations were randomly selected at least 1 meter from the edge of the plot in a representative location. Tillage radish was sampled in the November of each year before it winter killed. Cereal rye was sampled in the spring before it was chemically terminated. No biomass was collected from control plots at either the fall or spring plant samplings. Above ground cover crop biomass was sampled and shoots were separated at the soil surface. Dry weights of three 0.25m^2 quadrants were measured in each plot and used for nitrogen uptake determination and analysis. Corn plants were sampled at harvest each year and total tonnage was measured from the middle 6 rows of each plot. Corn subsamples were taken from each plot, oven dried at 55 C^o, ground and then analyzed for N concentration.   Ground samples were analyzed for %N using a combustion analyzer (FP523 N Analyzer, LECO St. Joseph, MI). Total N was used to establish N uptake for corn and cover crop plant samples. Nitrogen uptake was calculated by multiplying %N by total biomass (kg ha^{-1}).

Soil Sampling

In order to estimate the mineralization of N from cover crop residue, soil samples were collected every two weeks in the spring before corn planting and were analyzed for soil NO_3-N and NH_4-N. Three intact soil cores were collected from random locations in each plot to a depth of 0-20cm and combined to create a composite sample. All soil samples were immediately dried for 24 hours at 105 C^o and ground through a 1mm sieve before analysis. To determine NO_3-N and NH_4-N, a 5g subsample from each depth was shaken with 50 ml of 0.01M $CaCl_2$ solution, filtered with Whatman 42 filter paper, and analyzed using the Ion Chromatography and Ion Selective Diffusion respectively.

Statistical Analysis

Statistical analysis of soil inorganic N concentrations, cover crop and corn N uptake, crop biomass, and corn silage tonnage was conducted using ANOVA as calculated by SAS Proc Mixed (SAS I006Estitute, Cary NC). Block effects were treated as random variables while cover crop treatments fixed effects. Tukey Multiple Means comparisons were used to compare treatments to each other and to the control. Due to natural soil variability and number the of subsamples obtainable a P level of <0.10 was considered significant.

Results and Discussion

Weather, Soil Temperature and Soil Moisture Data

Soil mineralization and nitrification were examined in the spring of each year following the winter kill of tillage radish and the chemical termination of cereal rye. As expected, tillage radish winter killed by January of each year, thus it is important to understand the differences in temperature and precipitation from January up to corn planting. This examination will allow us to investigate the influence weather has on mineralization of cover crop residue. The average air temperature from January 2012-April 2012 was 6.13 C$^{\circ}$ compared to 1.04 C$^{\circ}$ during the same period in 2013. For instance, the months of February, March and April of 2012 were 3.50, 12.50 and 2.61 C$^{\circ}$ warmer relative to the same months in 2013, respectively. Like air temperature, monthly precipitation was different between January-April 2012 and 2013. In the first year (2012), there was 160.02 mm less total precipitation than the second year (2013). For example, the months of January and April of 2012 had 53.59 and 56.13 mm less precipitation than the same months in the second year.

In the spring of 2012 and 2013, soil temperature and moisture were measured on each soil sampling date to better understand soil mineralization and nitrification. In both years, there were no detectable differences in soil temperature and moisture among treatments. However, soil temperature and moisture were different between years. The average soil moisture in the spring of 2012 (Late March – Late April) was 25.3% and the average soil temperature was 11.4 C$^{\circ}$. For the same time period in the spring of 2013, the average soil moisture was 30% and average soil temperature was 7.6C$^{\circ}$. Soil temperature and moisture data in 2013 were measured into mid-May because of delayed corn planting. In May 2013, average soil temperature was 15.7 C° and average soil moisture was 26.6 %.

Variable weather conditions between the springs of 2012 and 2013 allowed for the evaluation of the impact of cover crops on soil mineralization and nitrification under two weather extremes. In the spring of 2012, warmer soil temperatures led to more soil mineralization and nitrification taking place. This agrees with Szukics et al. (2010) whom found that the rate of soil nitrification increases as soil temperature increases. In contrast to 2012, in the spring of 2013 soil temperatures below 10 C° reduced the rate of soil mineralization and nitrification. In general, differences in spring weather influenced soil temperature and moisture conditions which impacted the amount of soil mineralization and nitrification that took place each spring.

Cover Crop Shoot Dry Matter and Nitrogen Uptake

In the 2011/2012 growing season tillage radish accumulated 6,561.9 kg ha^{-1} dry matter and absorbed 226.8 kg N ha^{-1} of total N uptake. In the 2012/2013 cover crop season, tillage radish had significantly less biomass (3,707.5 kg ha^{-1}) and N uptake (131.9 kg N ha^{-1}). Cereal rye accumulated 3,906.5 kg ha^{-1} dry matter in the 2011/2012 growing season and absorbed 188.1 kg N ha^{-1} dry. In 2012/2013 season, cereal rye had significantly greater biomass (5585.5 kg ha^{-1}) and N uptake (249.9 kg N ha^{-1}).

Both tillage radish and cereal rye had significantly different biomass and N uptake values between the first and second cover crop growing season. It is likely that the variability in weather impacted the growth of both cover crops. Colder air temperatures in late September, October, and November 2012 relative to 2011 likely contributed to less tillage radish biomass and N uptake. Cereal rye was less affected by colder air temperature and grew vigorously in the fall and spring of each year. However, despite the differences in weather tillage radish and cereal rye demonstrated the ability to absorb nearly the full rate of N applied in the fall. In fact, when averaged over 2 years of the study tillage radish and cereal rye N uptake were 179.4 and 219.0 kg ha^{-1} respectively (90 and 110 % of N that was fall applied). This observation is vital because sequestered N is less vulnerable to loss since it is assimilated into the cover crop biomass and not susceptible to leaching or denitrification.

Spring Soil Mineralization and Nitrification

Variable weather conditions between the springs of 2012 and 2013 allowed for the evaluation of the impact of cover crops on soil mineralization and nitrification under two weather extremes. The spring of 2012 was relatively warm and dry compared to the spring of 2013. As a result of warm weather, soil temperatures in 2012 were 3.8 C◦ warmer than in the spring of 2013. Thus, in the spring of 2012, soil NH_4-N was not significantly different between treatments on either sampling date. However, over the same time period soil NO_3 –N concentration significantly increased between the first and last soil sampling dates (41 days after cereal rye termination) by 152.1, 71.361, and 56.3 kg ha^{-1} for tillage radish, cereal rye, and the no cover crop control, respectively. Furthermore, tillage radish significantly ($P< 0.08$) increased soil NO_3-N by at least 97.1 kg ha^{-1} relative to all other treatments, 28 days after cereal rye termination.

In contrast to 2012, in the spring of 2013 fall applying N into tillage radish resulted in significantly more soil NH_4-N (137.7 kg ha^{-1}) compared to both the control (24.7 kg ha^{-1}, $P=0.02$) and cereal rye (66.7 kg ha^{-1}, $P=0.06$). At the same sampling date, fall application into tillage radish resulted in significantly greater NO_3-N relative to the control plots (41.2 kg ha^{-1}, P=0.06) and cereal rye plots (43.3 kg ha^{-1}, P=0.05). Additionally, 20 days after cereal rye termination, the control resulted in significantly more soil NO_3-N compared to cereal rye ($P \leq 0.10$, 16.3 kg ha^{-1}). Furthermore, 29 days after cereal rye termination, tillage radish plots had significantly greater soil NH_4-N then control plots (P=0.03, 21.1 kg ha^{-1}).

In the spring of 2012, soil temperatures above 10 C° resulted in increased mineralization of tillage radish residue followed by rapid nitrification of mineralized NH_4-N. Rapid nitrification contributed to consistently greater soil nitrate in tillage radish plots compared to control and cereal rye plots. In contrast to 2012, soil temperatures below 10 C° in April of 2013 reduced the rate of soil nitrification. As a result, a greater concentration of mineralized NH_4-N was observed. However, from April to May 2013 soil temperatures rose above 15 C° and the plots received 156 mm of precipitation. Thus, soil NH_4-N in tillage radish plots decreased by 101.4 kg ha^{-1} potentially due to nitrification or N loss by leaching or denitrification. This finding agrees with Vyn et al. (1999) who suggested that early N mineralization from oilseed radish residue was lost by dentrification and leaching. Similarly, in Maryland researchers found that early mineralized N from forage radish resulted in increased spring nitrate leaching on sandy soils (Dean and Weil, 2009). Another cover crop mineralization study in the Netherlands observed soil inorganic N from May through July and concluded that the increases in inorganic N were a result of mineralization of natural organic matter, not from the mineralization of forage radish (Vos van der Putten, 2001). However, our data indicates that in two weather extremes mineralization of tillage radish residue directly increased soil inorganic N immediately before planting cash crops.

Consistently lower soil nitrate concentrations in cereal rye plots compared to tillage radish and control plots are potentially the result of 3 factors. First, cereal rye has a much later termination date then tillage radish and therefore there was less time for cereal rye residue to mineralize each spring. Second, a higher C/N ratio of cereal rye biomass compared to tillage radish potentially slowed the rate of cereal rye mineralization. Third, cereal rye residue with a C/N ratio above 30/1 can lead to microbial immobilization soil inorganic N (Dean and Weil, 2009). Visual observations illustrated, that by corn planting, little mineralization of cereal rye biomass had occurred. In agreement with our results, Adeli et al. (2011) concluded that lack of N mineralization from winter rye biomass reduced available N in the soil. This is a potential benefit to farmers because N sequestered in cereal rye biomass is much less vulnerable to loss then soil N or early mineralized N from tillage radish residue.

Silage Yields

Corn silage data was collected from the middle six rows of each plot at harvest each year and adjusted to 55% moisture content. Across both years fall applied nitrogen into a standing cover crop did not significantly impact corn yield or corn N uptake (Table 3) compared to the control. Draught conditions in summer of 2012 resulted in extremely low average corn yield across all treatment (18.8 Mg ha^{-1}) and average N uptake (127.3 kg N ha^{-1}). In contrast, the summer of 2013 had good growing conditions and resulted in nearly 3 time greater yield (51.3 Mg ha^{-1}) and two times more N uptake (267.9 kg N ha^{-1}).

In both years, tillage radish increased the amount of inorganic N available at planting compared to the control and cereal rye plots. Cereal rye slowly mineralized and potentially increased inorganic after corn planting. Despite these benefits there were no significant differences in silage yield in either year. It is likely that stress from drought conditions in the summer of 2012 limited our ability to detect any impact cover crop might have had on corn yield and N uptake. Excess residual N was present in the soil after harvest due to low N uptake by corn. In 2013, applying the full rate of fall N in addition to excess residual N resulted in an abundance of N available to the corn plant and any yield response from improved N management in the second year with cover crops was not detectable.

Conclusions

The mineralization and nitrification of fall applied N from cereal rye residue was slower compared to tillage radish. Less time for cereal rye to mineralize in the spring and a greater C/N ratio likely accounted for the slower release of fall applied N to the subsequent cash crop. As a result, N absorbed by cereal rye remained as organic N to be slowly released after planting of the cash crop. In contrast, rapid mineralization of tillage radish residue resulted in a 2 year average of 91% of the equivalent rate of fall applied N as inorganic soil N in the spring at the 0-20cm depth compared to 66% for the control and 55% for cereal rye plots.

Currently, the cover crop industry recommends terminating cereal rye three to four weeks before the expected cash crop planting date in order to benefit from mineralize N from cereal rye residue. However, the data suggests that this termination date does not allow enough time for the mineralization of absorbed N in cereal rye to occur. Therefore, there is a need to examine cereal rye and other cover crop species impact on soil mineralization into the cash crop growing season. This would allow farmers to better synchronize mineralization and N release from cover crop residue with the growth stages of the subsequent cash crop.

As expected, with several months to decompose for winter kill cover crops, like tillage radish, the spring release of mineralized N was greater. This early release of N could be a concern because of the potential for N loss by leaching or denitrification. One potential solution to this concern is planting a mixture of winter kill and over wintering cover crops species, the presence of a growing cover crop in the spring might reduce the susceptibility of early mineralized N to loss.

Despite variable weather across both experimental years, fall application of N into cereal rye and tillage radish demonstrated the potential to take up the full rate of fall applied N, stabilize N near the soil surface, which improves the effectiveness of fall applied N.

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APPENDIX A

TABLES FOR CHAPTER III

Impact of Cover Crops on Nitrate Leaching Following Fall N Application

Table 1.) Below is a table of important dates such as: sampling, planting, harvest, and fertilizer application.

	Main Crop Year		
Field Activity	**2011**	**2012**	**2013**
Spring Cover Crop Sampling		Mar. 17	Apr. 07
Cover Crop Termination		Mar. 21	Apr. 09
Spring Soil Sampling		Apr. 03	Apr. 05
Spring Tillage		Apr. 03	May 09
Main Crop Planting Date		Apr. 23	May 15
Vt Corn Sampling		Jul. 06	
Harvest Sampling		Aug. 24	
Cover Crop Planting Date	Sep. 08	Sep. 13	
Fall Soil Sampling	Sep. 20	Sep. 20	
Fall Cover Crop Sampling	Nov. 15	Nov. 27	
Fall N Fertilizer Date	Nov. 15	Nov. 19	

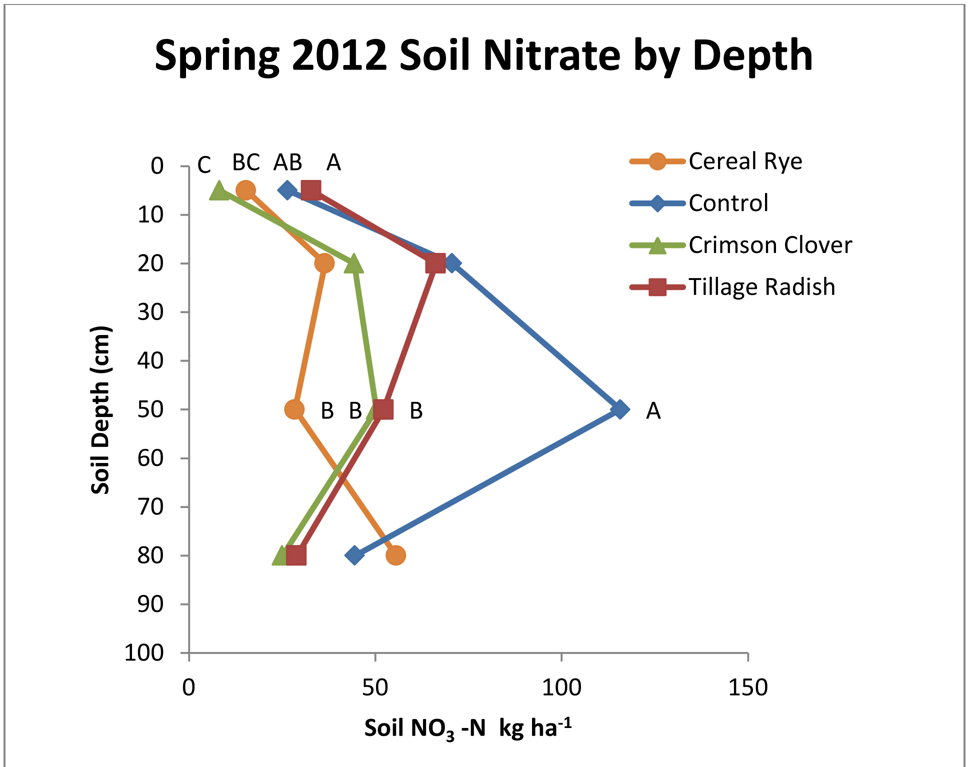


Figure 1. Soil nitrate (kg N ha^{-1}) by depth (cm) collected in spring of 2012. Different letters as each depth indicate significant difference at an alpha level of 0.10.

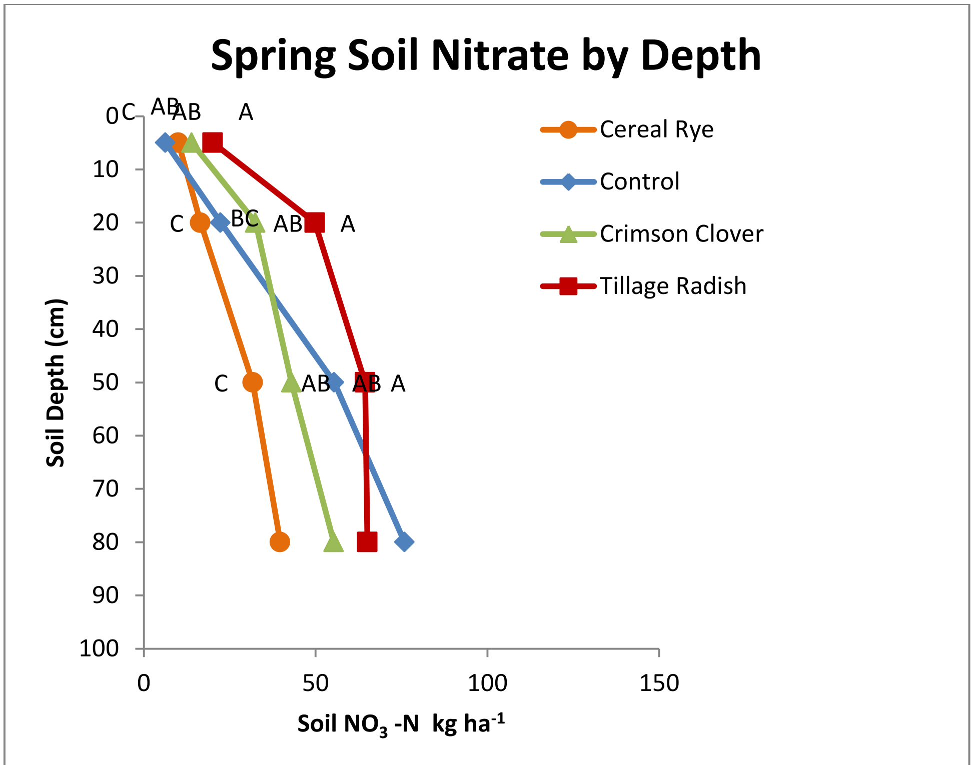


Figure 2. Soil nitrate (kg N ha^{-1}) by depth (cm) collected in spring of 2013. Different letters as each depth indicate significant difference at an alpha level of 0.10.

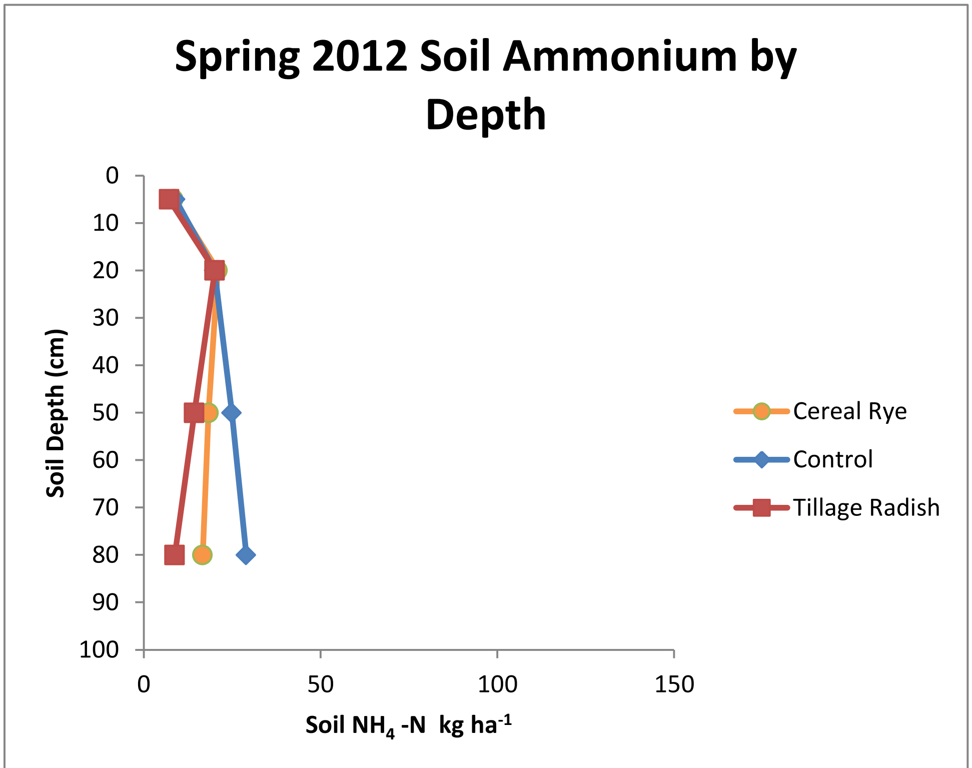


Figure 3. Soil ammonium (kg N ha^{-1}) by depth (cm) collected in spring of 2012. Different letters as each depth indicate significant difference at an alpha level of 0.10.

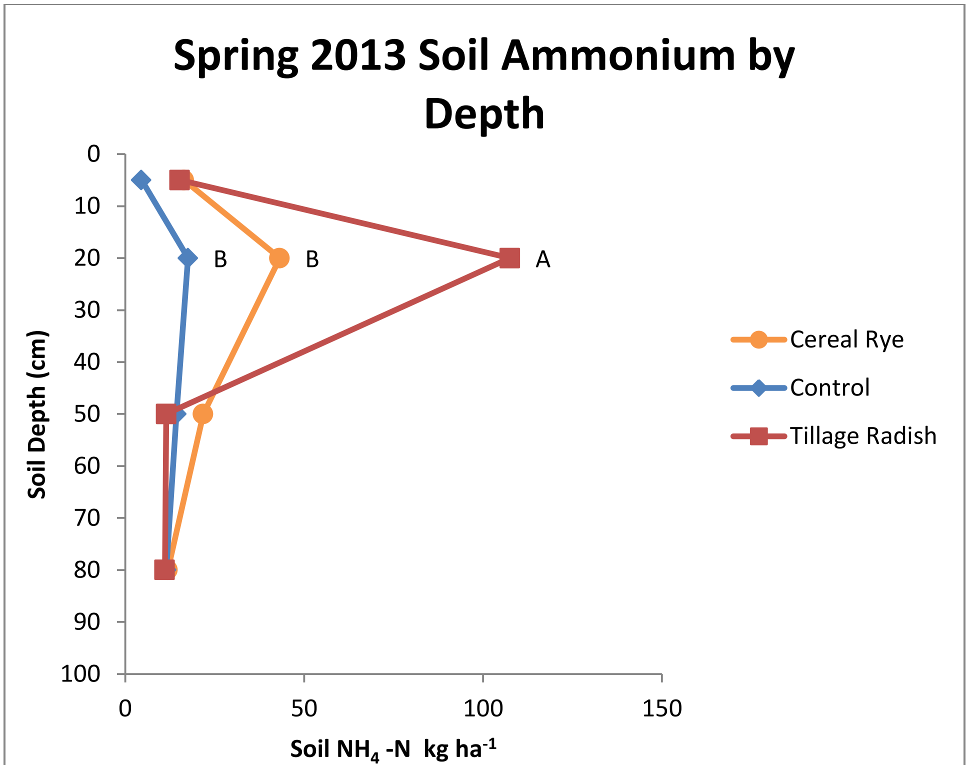
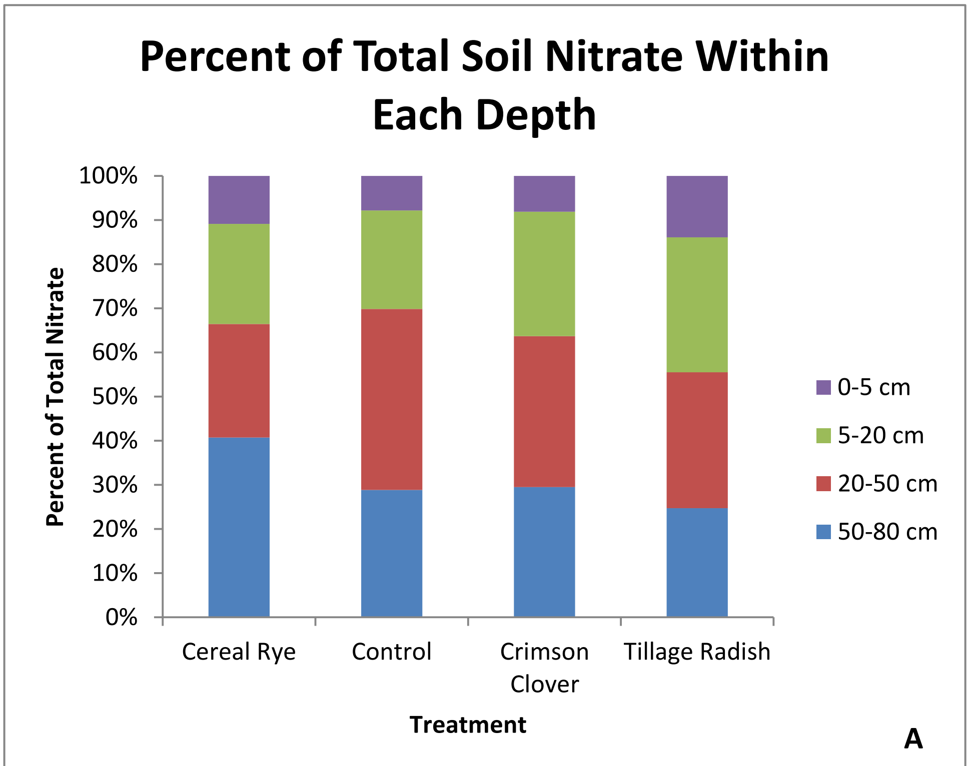


Figure 4. Soil ammonium (kg N ha^{-1}) by depth (cm) collected in spring of 2013. Different letters as each depth indicate significant difference at an alpha level of 0.10.



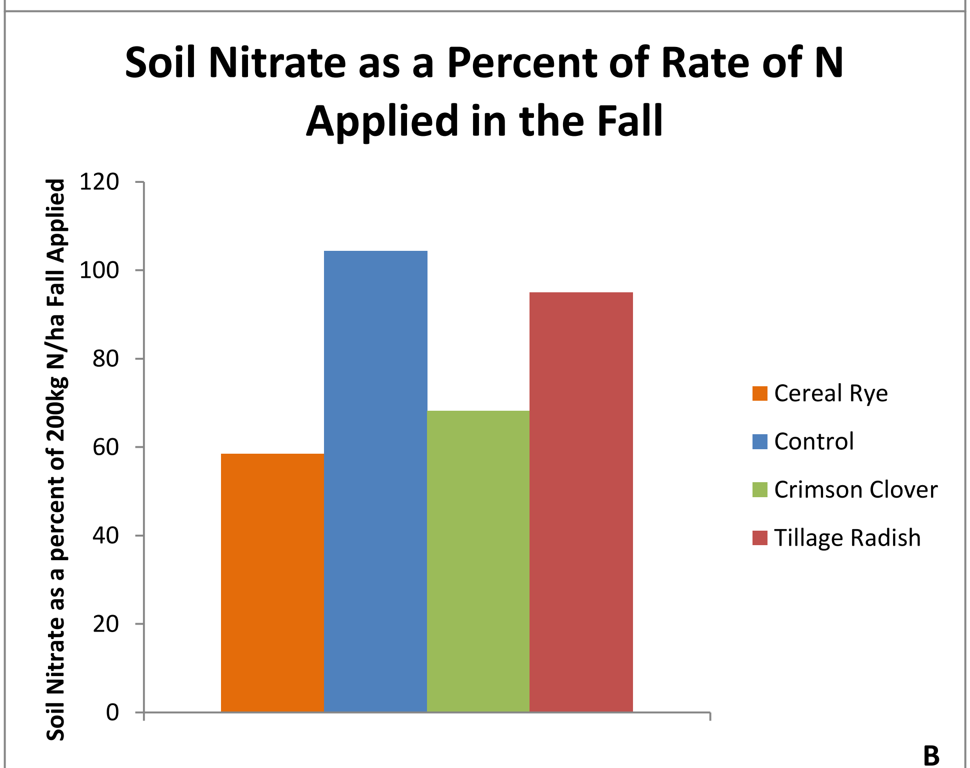


Figure 5. A.) Percent of total (0-80cm) soil nitrate found in each depth of the soil profile. B.) Total (0-80cm) soil nitrate a percent of the rate of N applied in the fall.

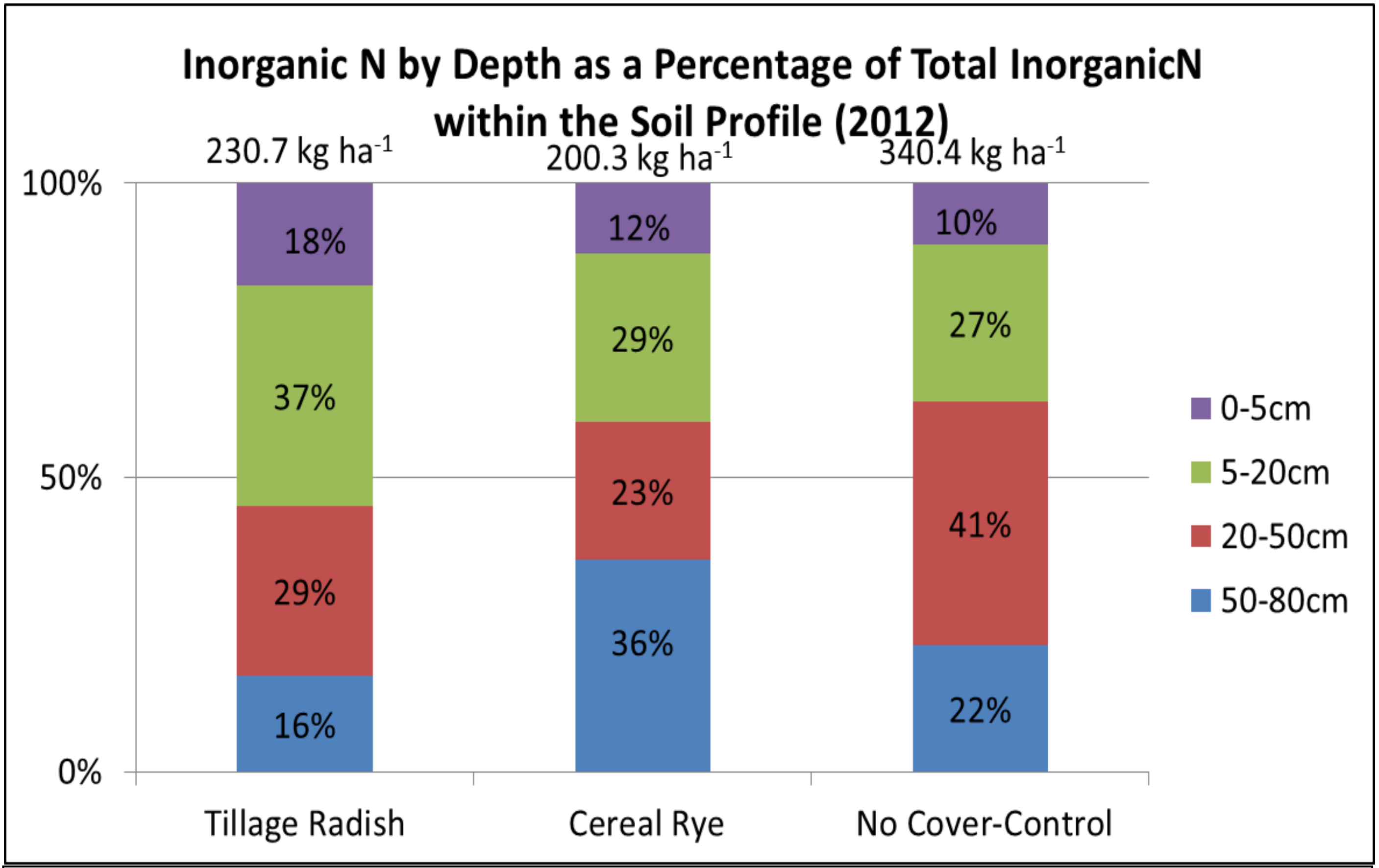


Figure 6: Soil Inorganic N as a percentage of all inorganic N within the entire soil Profile. Numbers on the top of each column represent the average total amount of inorganic N within treatment to a depth of 80cm.

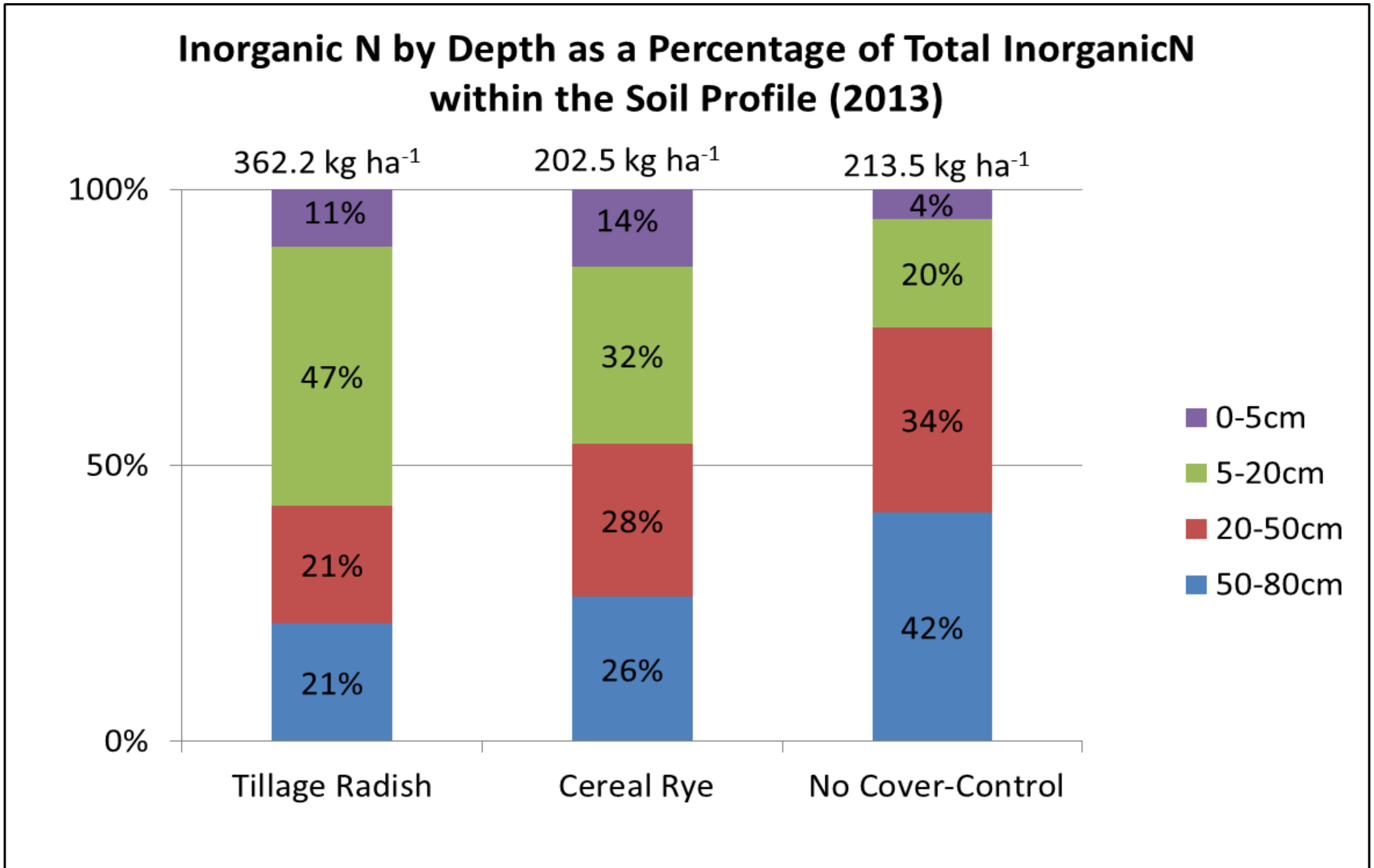


Figure 7: Soil Inorganic N as a percentage of all inorganic N within the entire soil Profile. Numbers on the top of each column represent the average total amount of inorganic N within treatment to a depth of 80cm.

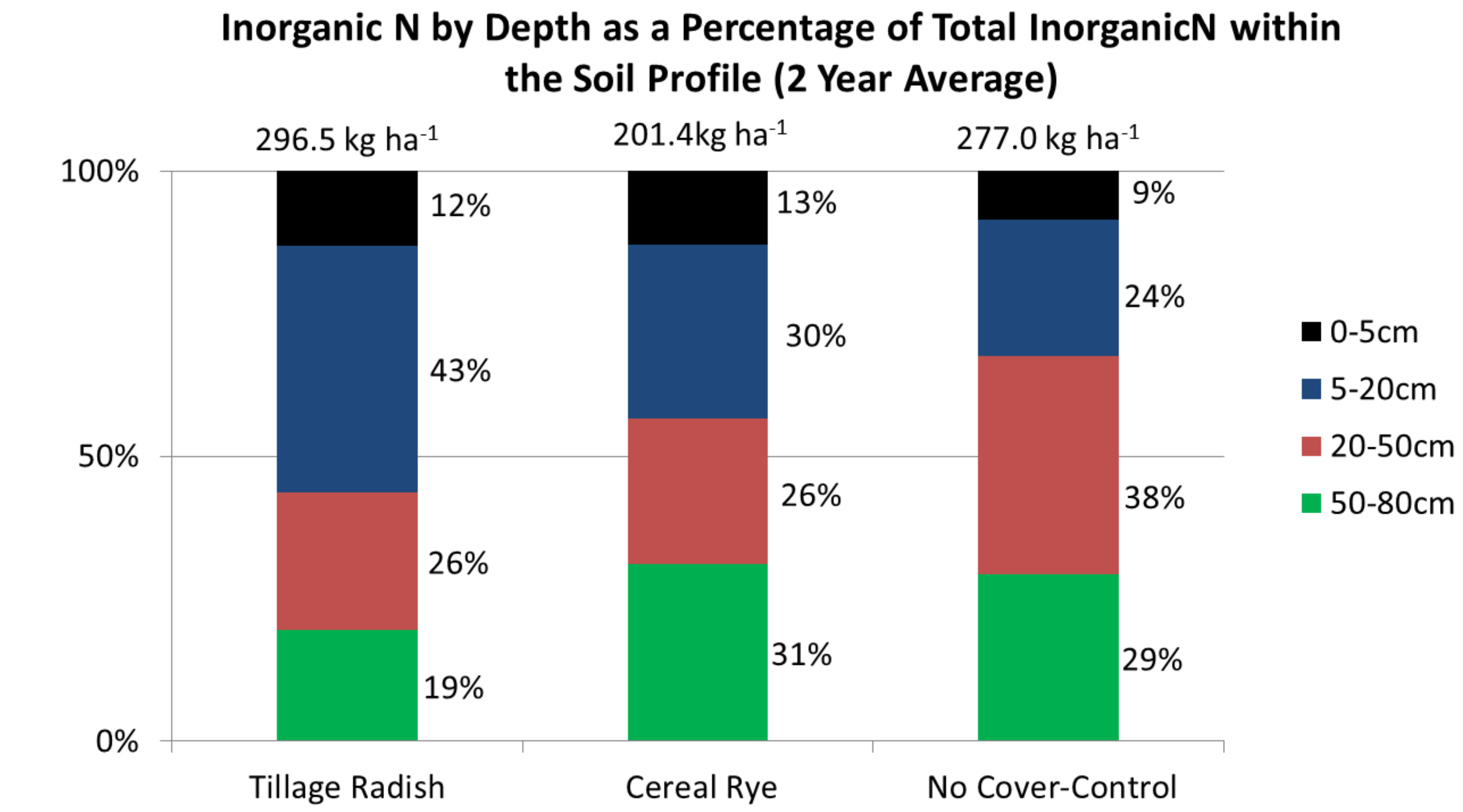


Figure 8: Soil Inorganic N as a percentage of all inorganic N within the entire soil Profile. Numbers on the top of each column represent the average total amount of inorganic N within treatment to a depth of 80cm.

APPENDIX B

TABLES FOR CHAPTER IV

In Field Measurement of Nitrogen Mineralization Following Cover Crop Termination

Table 1. Below is a table of important dates such as: sampling, planting, harvest, and fertilizer application.

	Main Crop Year		
Field Activity	**2011**	**2012**	**2013**
Spring Cover Crop Sampling		Mar. 17	Apr. 07
Spring Soil Sampling 1		Mar. 18	Mar. 30
Cover Crop Termination		Mar. 21	Apr. 09
Spring Soil Sampling 2		Mar. 28	Apr. 05
Spring Soil Sampling 3		Apr. 03	Apr. 15
Spring Tillage		Apr. 03	May 09
Spring Soil Sampling 4		Apr. 11	Apr. 29
Spring Soil Sampling 5		Apr. 18	May. 08
Main Crop Planting Date		Apr. 23	May 15
Spring Soil Sampling 6		Apr. 25	May 15
Harvest Sampling		Aug. 24	
Cover Crop Planting Date	Sep. 08	Sep. 13	
Fall Cover Crop Sampling	Nov. 15	Nov. 27	
Fall N Fertilizer Date	Nov. 15	Nov. 19	

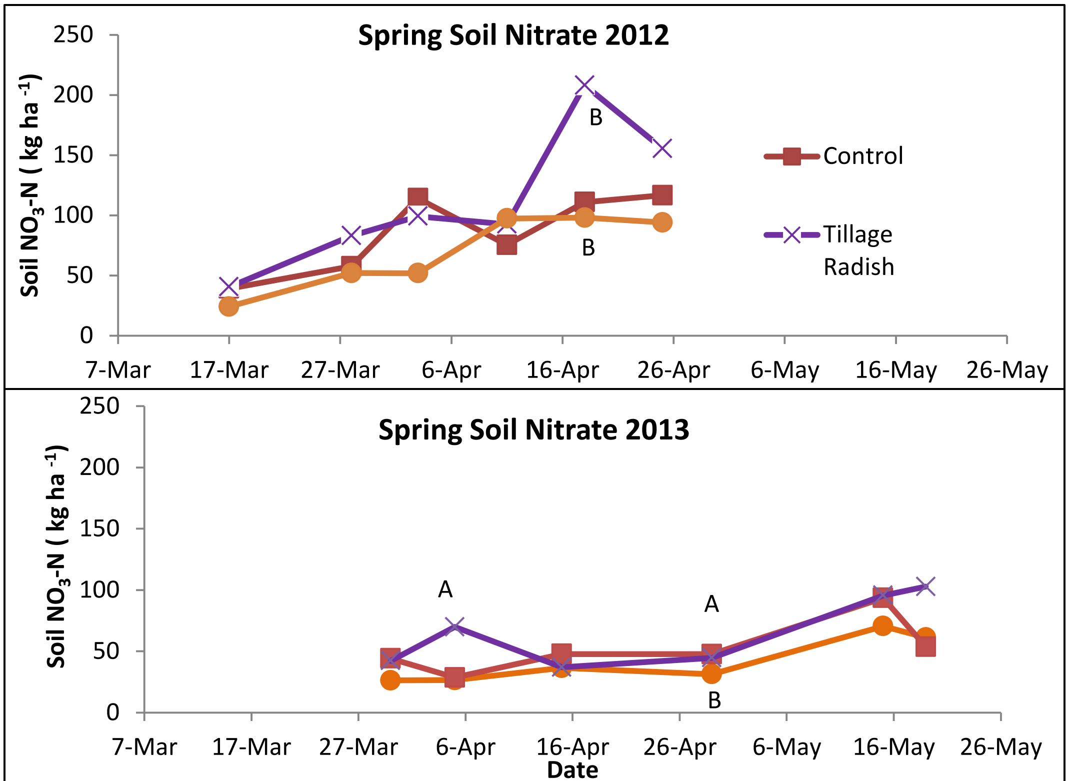


Figure 1. Spring soil nitrate (kg ha^{-1}) from both spring 2012 (Top) and 2013 (Bottom). Capital letters indicate significant differences ($P \leq 0.10$) between treatments within sampling date.

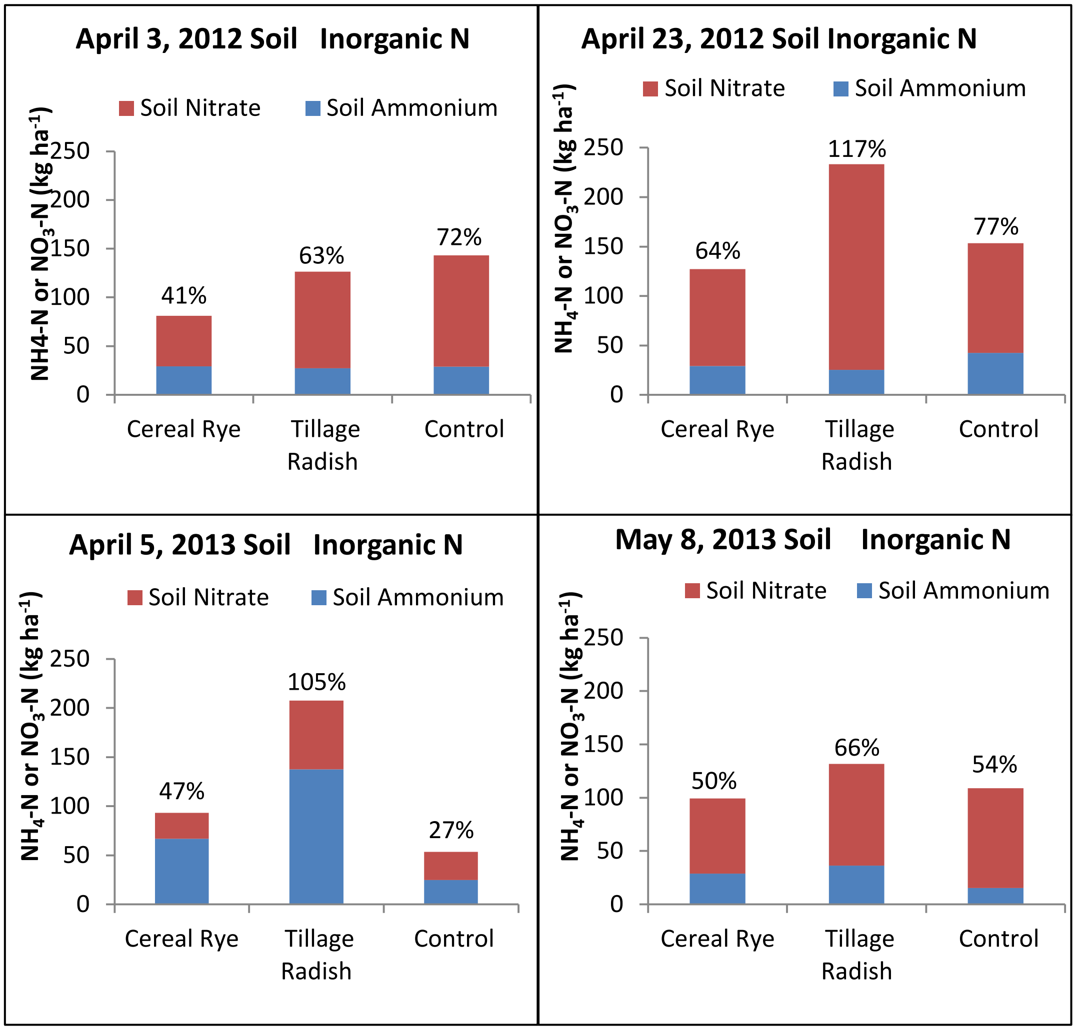


Figure 2. Total inorganic N at cereal rye termination (Left Top and Bottom) and at planting (Right Top and Bottom) for 2012 and 2013. The percentage on top of each bar represents the amount of inorganic N as a percentage of the fall N application rate (200 kg N ha^{-1}). Capital letters represent significant differences for ammonium between treatments within sampling date. Lower case letters represent significant differences for nitrate between treatments within sampling date.