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Winter Cover Crops Impact on the Distribution of Soil Inorganic Nitrogen and Subsequent Crop Uptake and Yield Following Fall Applied Anhydrous Ammonium

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WINTER COVER CROPS IMPACT ON THE DISTRIBUTION OF SOIL INORGANIC NITROGEN AND SUBSEQUENT CROP UPTAKE AND YIELD FOLLOWING FALL APPLIED ANHYDROUS AMMONIUM

William T. Deppe

151 Pages

This thesis is a comprehensive analysis of research, investigating the impact of cover crop integration and fall applied nitrogen at various rates on the susceptibility of total inorganic nitrogen, nitrogen uptake and crop yield.

KEYWORDS: Ammonium, Application rate, Corn, Corn yield, Cover crop, Critical growth stage, Fall applied anhydrous ammonium, Hypoxia, Illinois, Inorganic nitrogen, Mississippi river basin, Nitrate, Nitrogen uptake, Nutrient loss reduction strategy, Soil profile

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WILLIAM T. DEPPE

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CHAPTER I

INTRODUCTION AND BACKGROUND

Environmental, and economic concerns have stemmed from the association of Upper Mississippi River Basin (MRB) agriculture and nitrate leachate. This connection between nitrate loss from agriculture fields and the eutrophication (hypoxia) in the Gulf of Mexico has become inherently clear (Alexander et al., 2000). Hypoxic zones are areas of low dissolved oxygen that occur in oceans and lakes due to excess nutrient loading (Helly and Levin, 2004). In response to these water quality issues, the United States Environmental Protection Agency (EPA) have developed a nutrient reduction strategy to lessen the total nitrogen and phosphorus loading by 45%, with an embedded goal to diminish hypoxia dimensions within the Gulf to a total of 5,000 Km^2 (David et al., 2014). Nitrate (NO_3^-) is the form of nitrogen with the highest degree of focus. This is because a number of studies have consistently established that NO_3^- is the dominant form of nitrogen existing within the soil water, due to the lack of a positive charge and physical interaction with the soil particles (Jacinthe et al., 1999). According to Goolsby the amount of nitrate loading delivered to the Gulf of Mexico has nearly tripled since the 1950's (Goolsby et al., 1999). The Mississippi River annually contributes 1.57 million metric tons of NO_3^- to the Gulf of Mexico. Multiple studies approximate up to 81% of the total nitrogen flux are a derivative of agriculture. Leachate as subsurface flow and runoff as overland flow have been directly linked to 63% of the total, while atmospheric deposition (deposition of nitrous oxides from continuous consumption of fossil fuels) contributes about 18% of the 1.57 million metric tons (Alexander et al., 2000).

MRB agriculture has been recognized as one of the primary influences for the increase in NO_3^- pollution of surface and subsurface waters due to the increased use of inorganic fertilizers in association with the removal of livestock and crop rotation diversity as primary cultural practices (Keeney and DeLuca, 1993). The effects of NO_3^- loading are enhanced by the use of fall applied nitrogen fertilizers. Fall applied nitrogen fertilizer increases nitrate leaching compared to fertilizer that was applied in the spring. The application timing directly impacts the availability of that nutrient source during the growing season (Randall, 2005). However, many producers still choose to apply nitrogen in the fall due to lower fertilizer costs, better field conditions, and pre-plant time constraints (Smiciklas et al., 2008). Current nitrogen management practices including timing, rate and methods combined with a decrease in crop rotation diversity has been linked to increased nutrient loss and soil health degradation. Diversity can be achieved by employing annual and perennial crops in conjunction with a standard row crop rotation; as a result, decreasing the potential for eutrophication of immediate crop nutrient and water resources (Kanwar et al., 1993).

One nitrogen management system that has been proven to reduce the leaching potential and improve N use efficiencies is the inclusion of winter annual cover crop species. Cover crops, if employed correctly, could help to reduce pollution from excess residual and inorganic applied nitrogen (Danso et al., 1991). Certain cover crop species are characteristically grown with the purpose of scavenging as much available nitrogen from the soil as possible. Once sequestered, the nitrogen within the biomass of the cover crop is released back into the soil as it begins to decompose (Ditsch and Alley 1991). Seeding cover crops after the harvest of a previous cash crop can effectively utilize residual nitrogen pools. More research is needed on the implementation of such cover crop species into current nitrogen management systems.

To our knowledge there has been little research done on the impacts of cover crops on a fall nitrogen management system within the MRB. The majorities of the documented cover crop integration research has utilized unconventional application methods to document their benefits and were conducted in different climatic regions. According to a study conducted by Lacey and Armstrong, 2013, cover crops have the capacity to impact the distribution of inorganic nitrogen within the soil profile in a silage cropping system at a single fall nitrogen application rate (Lacey and Armstrong, 2013). Therefore, there is a dearth of knowledge in regard to the relationship between certain cover crop species and the efficacy of fall applied nitrogen at various rates in a commercial practice. The purpose of this study is to assess the effects of cover crops and alternate application rates in a row crop (corn) situation in order to improve the efficacy of the fall applied nitrogen management system.

Research Hypotheses

1. All cover crop treatments will have reduced soil nitrate (NO_3-N) concentration at lower depths and increased soil ammonium (NH_4-N) concentrations at the upper depths versus the no-cover control.
2. All cover crop treatments will increase the percent of the total N uptake at each critical crop development stages than in the no-cover control, along with a subsequent increase in grain yield.

Research Objectives

1. Investigate the efficacy of winter cover crops to impact the distribution of soil inorganic N following fall applied anhydrous ammonia.
2. Determine the applied effects of cover crops on overall grain yield and crop uptake at critical growth stages when employing alternate application rates.

CHAPTER II

LITERATURE REVIEW

Nitrogen Management Systems within the Upper Mississippi River Basin

States within the upper Mississippi River Basin (MRB) have been vital for overall corn and soybean production in the United States. In 2012, Iowa, Illinois, Indiana, Minnesota and Nebraska accounted for 60% of the total corn kg/ha^{-1} harvested (USDA, 2012). In 2009, those states also produced more than 80% of the total (31.5 million hectares) soybean hectares within the United States according to the USDA (2009). Producers within this region predominately implement a corn-soybean crop rotation. However, based upon a model projected by the USDA-ERS Regional Environmental and Agriculture Programming (REAP), continuous corn will represent approximately 30% of the corn ha^{-1} in the United States by 2015. This increase is directly correlated with potential for higher overall return on investment (ROI) due to inflated market prices (Malcolm, 2009). Conversely, research has indicated that yield declines in these types of systems, when compared with conventional corn-soybeans rotations (Gentry, 2013). The removal of soybeans from the rotation also introduces increased annual fertilizer needs; particularly nitrogen. The nitrogen requirements of corn are generally met by the use of inorganic fertilizer, unlike soybean, which have the capacity to fix atmospheric nitrogen. This adds complexity to the management system within this region and further compounds nitrogen (N) loading to local water bodies. Crop selection within this region is predominately driven by the dominant soil type present and weather patterns experienced throughout the growing season.

The aforementioned Upper Mississippi River Basin area has been described by the USDA as prime farmland, or land that has the best combination of physical and chemical characteristics for producing food, feed, forage, fiber and oilseed crops. The predominant soil order found within this highly fertile region are Mollisols. In the United States, Mollisols are one of the most extensive soil orders, accounting for approximately 21.5% of the total land area (McDaniel). This soil order is defined as a soil of grassland ecosystems; characterized by a thick, dark surface horizon (>25 cm thick). “This fertile surface horizon, known as a mollic epipedon, characteristically forms under grass (prairie) in climates that have a moderate to pronounced seasonal moisture deficit” (Soil Taxonomy- USDA-NRCS). Theses soils have a naturally high OM content; approximately 3-6% according to Hargrove and Luxmore (1988) high-resolution, national soil organic matter (SOM) map. The natural fertility of the Mollisol soil class that contributes to crop productivity, also influences the NO_3^- loading potential to surface water.

USDA soil texture maps illustrate these highly productive (nitrogen rich) regions within the Mississippi river basin. The predominant soil textural class is silt loam/silty clay loam soils (USDA-NRCS). This textural class of soil is indicative of relatively high clay content, typically dominated by 2:1 layer silicates (Allen and Fanning, 1983). The approximate content of various particle sizes and OM content within the Mollisol soil matrix significantly influence the water infiltration rate, soil permeability and water holding capacity. The dynamic properties of a Mollisol directly influence water movement and drainage capability, therefore governor the rate at which nitrates (NO_3^-) are removed via leaching and denitrification processes. The drainage classification of two states within this region (Illinois and Iowa) have been categorized as average drainage capacity, with many regions that range from excessively drained to poorly drained based upon soil class (USDA-NRCS 2012). The presence of artificial drainage increases the overall rate at which water and nutrients are transported through the soil profile, to be discharged to surface water (Carlson et al., 2011). A study conducted by Moorman et al (2004) showed how an Iowa watershed annual nitrate loss via artificial tile can vary from 4 to 66 kg/ha^{-1} dependent upon events of precipitation.

The average annual precipitation (rainfall) within this region increase directionally, from north to south, ranging from approximately 50 cm in northern Minnesota to 120 cm in the southernmost part of Missouri. Peak monthly precipitation totals generally occur during the spring and summer months. A direct correlation has been made with substantial rainfall events during these warmer months and excessive NO_3^- movement to surface waters. However, this relationship is not noted when regional precipitation is at its lowermost point. The average annual snowfall amount can vary from <25 cm in the southern part of the region to > 500 cm in northern Michigan. Winter recharge of soil moisture is partly dependent upon annual snowfall totals; however, the fundamental dynamic (freeze-thaw cycle) is primarily temperature driven (Andresen et al., 2012).

Average annual temperatures within the MRB can vary by ~12°C across the region. The temperatures can range from 3.5°C to 15.5°C in Northern Minnesota to Southern Missouri respectively (Andresen et al., 2012). Seasonally, the temperatures across this region peak in the latter part of July or early August. Due to temperature flux within the region, a temperature-derived index (growing degree day-GDD) of time spent at or above the 10 degree (°C) threshold is used to determine the amount of "Heat Units" received on a daily or annual basis. Growing degree days on an annual basis can range from 2000-4000 in northern Michigan and Minnesota to southern Missouri and Illinois respectively (Andresen et al., 2012). The quantity of heat units received during a growing season is the primary catalyst that induces natural mineralization and nitrification, (conversion of NH_4^+ to NO_3^-) these processes significantly contribute to nitrate leaching below the root intercept zone of the cash crop. Each of the crops grown within the river basin have a specific temperature and precipitation range characterized by upper and lower limits that regulate overall growth of the crop (Hatfield et al., 2011). It is difficult to select "a one size fits all" approach to fertility management based upon the amount of weather variability and current crops grown within the region that contribute to varying volumes of seasonal N loading.

A five-year study on nitrogen timing was conducted by Dr. Ken Smiciklas, in which Lake Bloomington, Illinois watershed producers were surveyed to estimate the average timing of their nitrogen application. The study determined approximately 55% of the cumulative producers within the watershed primarily utilized fall application methods. Another 32% of the producers used spring application as their primary application method, and 13% of the producers utilized multiple application timing (Smiciklas et al., 2008). According to numerous publications, spring N application has generally resulted in greater yield (kg/ha^{-1}) when directly compared with applications completed in the fall (Vetsch, 2004; Randall, 2005). However, this variance in yield is only significant when temperature and rainfall values are seasonally abnormal. Large rainfall events result in a sizeable reduction of plant available nitrogen caused by excessive leaching throughout the soil profile in either application systems.

Environmental Impacts of Current Nitrogen Management Strategies

National Impact

Environmental, and economic concerns have stemmed from the association of MRB agriculture and NO_3^- leachate. Studies have consistently established that NO_3^- is the dominant form of nitrogen existing within the soil water, due to the lack of a positive charge and physical interaction with the soil particles (Jacinthe et al., 1999). Soil nitrogen is susceptible to multiple loss pathways that include leaching, denitrification and volatilization. These losses contribute to the unique challenge of N management to ensure adequate nitrogen availability at peak crop demand. For corn production, recommended nitrogen fertilizer rates are based on utilization efficiencies of approximately 60% for states within the MRB; however, suboptimal growing conditions can reduce this percentage to much lower levels (Chichester and Smith; 1978). The connection between nitrate loss from agriculture fields and the eutrophication (hypoxia) in the Gulf of Mexico has become inherently clear (Alexander et al., 2000). The Gulf of Mexico is currently the second largest hypoxic area in the world, and it is fed mainly by the Mississippi and Atchafalaya Rivers (Renaud, 1986; Rabalais, 2002).

Hypoxic zones are areas of low dissolved oxygen that occur in oceans and lakes due to excess nutrient loading, these oxygen depleted regions no longer have the ability to support aquatic or marine ecosystems (Helly et al., 2004). Nutrient loading of surface waters derived from the MRB is the primary reason why the Mississippi River has been connected with this seasonal hypoxic region within the Gulf of Mexico (Turner et al., 1994). According to Goolsby the amount of nitrate loading delivered to the Gulf of Mexico has nearly tripled since the 1950's (Goolsby et al., 1999). The Mississippi River annually contributes 1.57 million metric tons of NO_3^- to the Gulf of Mexico. Multiple studies approximate up to 81% of the total nitrogen flux are a derivative of agriculture. Leachate as subsurface flow and runoff as overland flow have been directly linked to 63% of the total, while atmospheric deposition (deposition of nitrous oxides from continuous consumption of fossil fuels) contributes about 18% of the 1.57 million metric tons (Alexander et al., 2000).

Using data from waste water treatment plants, the USDA estimates the cost of removing nitrate from U.S. drinking water supplies is over $4.8 billion per year. Agriculture's contribution of these nitrate loading costs are estimated to be $1.7 billion per year (Smith et al., 1997). The USDA has indicated that reducing nitrate concentrations in source waters by one percent could reduce water treatment costs within the United States by up to $120 million dollars annually (USDA, NRCS, 2006).

Local Impact

In response to the water quality and hypoxia concerns in the Gulf of Mexico, the United States EPA developed a watershed nutrient taskforce in 2008. This taskforce's primary goal was to develop a proactive management plan to reduce and mitigate N loading to surface waters to improve overall water quality and to control hypoxia within the Gulf (2008 Action Plan). The action plan that was developed in 2008 called for each of the 12 states within the Mississippi river basin to reduce the amount of nutrient loading respectively contributed to surface waters. In 2011 the U.S. EPA provided the basic framework for state plans (Illinois reduction strategy, 2015), which includes reduction goals and dates those goals are to be reached by (Table 1); due to annual load variability, progress will be measured based on a five year consecutive average.

Table 1

Watershed Milestones and Targets Reductions for Illinois

Nutrient	Phase 1 Milestones (%)	Target reduction (%)
Nitrate-nitrogen	15 % by 2025	45%
Total phosphorus	25 % by 2025	45%

Note. Data gathered from EPA, 2014

According to the Illinois EPA, voluntary implementation of best management practices (BMP) are expected to build on efforts currently underway by producers throughout the state and in watersheds with existing nutrient reduction plans in order to mitigate agricultural non-point source effluence. The EPA expects the implementation of the BMP to increase with additional outreach, education and incentives (Illinois nutrient reduction strategy, 2015). The nutrient reduction strategy listed best management practices such as the four R's: Right Timing, Right Rate, Right Source and Right Placement. Implementation could include riparian (vegetative) buffers, constructed wetlands, bioreactors and cover crops to potentially improve nutrient retention and reduce environmental degradation.

Nitrate Reduction Management Practices

The 4 R's

The basic practices for improving nitrogen use efficiencies are agronomic application rate, appropriate timing of applications, proper placement and the correct source (USDA, NRCS, 2006). Implementation of the four application components in appropriation to fulfill the needs of a growing crop can aid in reducing N loss to surface waters. The 4 R's as defined by the USDA:

- *Right Timing:* Applying nitrogen in a practical manner as close to the time that the cash crop needs it; as opposed to the season before the crop is planted.
- *Right Rate*: Applying an amount of nitrogen at a rate that accounts for all other sources of nitrogen, residual from previous crops, irrigation water, and atmospheric deposits.
- *Right Source:* Matching the correct fertilizer product with soil properties and what is essential to the crop. This is achieved by balancing applications of nitrogen, phosphorus, potassium, and other nutrients according to crop needs and available soil nutrients.
- *Right Placement:* Injecting or incorporating the nitrogen into the soil to reduce leaching and losses to the atmosphere (USDA, NRCS 2006).

Right timing. The timely application of nitrogen has received considerable research. Two dominant time frames that producers are able to implement their application methods within prior to the cash crop growing season; late fall and early spring. Late fall applications have been associated with possible yield reduction, due to prolonged periods of exposure to environmental factors before the plant can effectively utilize the nitrogen source present. Spring in-season applications can be employed to optimize the efficiency of the input applied. This is achieved by applying the fertilizer closer to the optimum date of nitrogen utilization (Scharf et al., 2002). However, a seven year study conducted by Randall and Vetsch in Michigan investigating the impact of N timing on nitrate leaching via subsurface flow; statistical significance was only found in one year when directly comparing fall versus spring N management strategies (Randall et al., 2003). Conversely, in a year (1999) with abnormally high temperature and precipitation values, spring application increased corn yield by 25% compared with fall application across four various tillage systems (Vetsch and Randall, 2004). Despite N loss potential and decreased corn yield, in some areas of the MRB approximately 50% of the nitrogen fertilizer is still applied in the fall. Considering the listed pitfalls of fall application, it does have potential benefits for the producer, including optimum conditions for field work, time and more evenly distributed labor and equipment demands (Bundy, 1986). In addition, prices are generally cheaper in the fall season than in the spring due to the greater general availability of the product (Smiciklas et al., 2008).

Right rate. Nitrogen fertilizer costs continue to be one of the most expensive and variable production costs for a corn crop. Traditionally, cultural practices followed the general precedent set by the previous generation of applying extra units of N based upon given field historical yield levels. This is no longer economically feasible, nor is it acceptable to obtain new environmental objectives set by the EPA (Camberato, 2012). According to the Illinois Agronomy Handbook, N rate recommendations in the past were based upon 1.2 pounds N bushel^{-1} of corn produced (Fernandez et al., 2009). This recommendation has since been revised due to the connection between over application of fertilizers and N loading to surface waters. Current research is promoting the use of such tools as the corn nitrogen rate calculator. This N rate development tool is based upon the concept of "maximum return to nitrogen" (MRTN). The MRTN is the point at which yield is optimized by considering economic factors such as average crop yield, corn and fertilizer prices for a given region (Fernandez et al., 2009). This economic return model was developed by Iowa State University to assist producers in making annual management decisions based upon current market scenarios (Fernandez et al., 2009). Economic optimum N fertilizer rates for corn grain production vary within the MRB. Currently, nitrogen rate recommendations for a corn crop are developed for large geographical regions and have customarily been used without any consideration of in field variability. It has been documented that variability in soil properties affect the transport of soil NO_3^- across an agronomic field (Bausch et al., 2001). However, producers continue to manage their fields with uniform and liberal applications of fertilizer due to the lack of understanding and technology to manage the variability that affects crop efficacy and overall economic return (Bausch et al., 2001).

Right source. The application of nitrogen is essential to produce high yielding cropping systems necessary to meet the needs of the continually growing population. The manufacture of industrially fixed nitrogen (Haber-Bosch) is advantageous for corn production within the MRB (Wortmann et al., 2004). However, due to the excessive use of such products, agriculture is considered one of the major sources of N loading to surface waters. Some of the common fertilizers used within the region include anhydrous ammonia (AA, 82% N), urea-ammonium nitrate solution (UAN, 28-32% N) and urea (46% N) (Scharf et al., 2006). The most prominent nitrogen fertilizer source used within the MRB is anhydrous ammonia (Scharf et al., 2006). According to the national agriculture safety database (NASD), anhydrous ammonia is one of the most efficient and commonly used N sources for row crop production despite the hazards of application (Baker, 1993). It contains the highest nutrient concentration of any fertilizer, it is one of the cheapest sources of N and the principal fertilizer to be applied in the fall. All of which have led to a dramatic increase in its use (Schmitt et al., 1993). In terms of safety of application, the other N sources outperform AA, which is why some producers prefer these products. Commercial fertilizer urea is generally broadcast applied as a solid granular product (Overdahl et al., 2015). However, this can still cause significant loss via volatilization if not incorporated by means of rainfall event (0.635 cm minimum) or tillage operation. Urea, once incorporated acts similarly to AA; nitrification occurs and presents the potential loss of plant available nutrients through leaching and denitrification processes (Overdahl et al., 2015). Urea-ammonium nitrate solution is the most prevalent liquid N fertilizer because it is safe to handle, and easily applied in side dress application scenarios (Nutrient Source Specifics, 2007). The benefit of UAN is due to the chemical composition of the solution; 25% of the total N is immediately available for plant uptake in the form of NO_3^-, while the remainder of the total N is slowly available as nitrification occurs (Nutrient Source Specifics, 2007). If UAN application is timely, loss is minimal due to rapid crop uptake during early vegetative growth.

Right placement. Accurate placement of the fertilizer source is considered essential to minimize nitrogen losses throughout the growing season. There are many application methods for nitrogen, including broadcast application, surface banding and direct injection. Broadcast applications are most often coupled with a dry urea fertilizer.

However, broadcast applications can result in substantial loss via volatilization. Atmospheric loss of a broadcasted fertilizer is generally avoided by means of fertilizer incorporation, accomplished primarily via tillage tool (Scharf et al., 2006). Surface banding of nitrogen can be useful when the source of nitrogen used is a UAN solution applied within a field with dense residual cover. This application method is rarely used, only when the producer has a lack of equipment necessary to properly inject the nitrogen source. Direct injection is the primary method of nitrogen application within the river basin for both anhydrous ammonia and UAN fertilizers (Scharf et al., 2006). Fall injection of anhydrous ammonia has been viewed as one of the primary contributors of non-point source N loading of local water bodies. This is due to the volatility of the product and the length of time that the nitrogen source is exposed to environmental factors before the plant can utilize it.

Tile Water Interception

Riparian buffers. According to the nutrient reduction strategy, one established nitrogen management practice is implementing riparian buffers. The USDA defines a riparian buffer as a band of herbaceous plants parallel to a river, stream or water body. The primary purpose is to protect near-stream soils from over-bank flows, trap harmful chemicals and prevent the eutrophication of streams by surface and subsurface flow. Subsurface flow from agricultural fields containing NO_3^- , to be effectively removed from the system must pass through the riparian rhizosphere. Once the NO_3^- have reached this zone, the NO_3^- may either be absorbed by the plant roots and utilized for plant growth, or converted into a gaseous form of nitrogen by soil borne denitrifying bacteria (Riparian Buffers, NCSU, 2015). Riparian buffers have been repeatedly documented as having the potential to effectively remove NO_3^- from shallow ground waters. Clausen et al., (2012) found that the addition of a riparian buffer significantly reduced NO_3^- concentrations (52%) in ground water via vegetative assimilation and denitrification. This reduction was primarily documented within the 2.5 m downslope wetland adjacent to the stream; the remainder 30 m upslope portion of the buffer had minimal impact on the ground water concentration. This is evident because riparian buffers placed within areas with high water tables, high levels of organic carbon and more aerobic conditions have been found to have much greater rates of denitrification (Jacobs and Gilliam, 1985).

Constructed wetlands. The integration of a constructed wetland (non-historical wetland) is a BMP that has similar documented effects on NO_3^- concentrations as riparian buffers. However, unlike riparian buffers which utilize root intercept to reduce nitrate concentrations, the primary mechanism of nitrate removal within a constructed wetland is denitrification. This process typically accounts for 60-95% of the removed concentration (Spieles and Mitsch, 2000). As defined by the United States Environmental Protection Agency (EPA), constructed wetlands are "artificial wastewater treatment systems consisting of shallow (usually less than 1 m deep) ponds or channels which have been planted with aquatic plants, which rely upon natural microbial, biological, physical and chemical processes to treat wastewater and non-point sources" (U.S. EPA, 1993-2000).

These wetlands are engineered to approximate the water-cleansing process of natural wetlands. Crumpton et al., (1995) conducted a study on constructed wetlands and nitrate removal rates via denitrification and aquatic plant biomass assimilation. The study estimated that the eutrophication of subsurface ground water from a 100 hectare (ha) field producing corn could potentially be removed by 1 ha wetland. However, the author also noted that a wetland of this size would be limited during events of substantial rainfall. This is due to the necessary residence time needed for the microbial population to complete the denitrification process with the increased quantity of nitrate present within the wetland (Crumpton et al., 1995).

Bioreactors. Bioreactors, another listed EPA nitrate loss mitigation tactic similar to constructed wetlands; this BMP also primarily achieves nitrate remediation via denitrification processes. As defined by the USDA-NRCS (2012) a bioreactor is "a structure containing a carbon source (ex. woodchips) installed to intercept subsurface drain (tile) flow or ground water, and reduce the concentration of NO_3^-". Providing the microbial population with an ample supply of carbon in conjunction with anaerobic conditions offers the optimal environment for nitrate removal from subsurface (tile) flow to be achieved (Christianson et al., 2011). According to a study conducted by Woli et al. (2010) in Illinois, a bioreactors has the potential to remove a wide range of reactive nitrogen from the field tile system (23-98%). This wide range of removal efficiency is evidence that nitrate removal performance of bioreactors are influenced by a range of natural factors. A study from Iowa showed that temperature, NO_3^- influx concentration and residence time were the driving factors for percent N removal rate and overall N load reduction (Christianson et al., 2012).

The inclusion of any of the aforementioned best management practices into MRB conventional cultural practices would aid in the reduction of NO_3^- in groundwater. However, through the remediation of non-point source delivery to surface waters, anthropogenic N_2O emissions currently derived from the agriculture industry could potentially increase beyond the current 50% contribution (Bakken et al., 2012).

Cover Crops

Function. A cover crop is defined as a crop grown outside the primary growing season in order to prevent the loss of soil via erosion, increase biodiversity, and increase soil quality and fertility (Reeves et al., 1994). The concept of a living mulch cover crop was first evident in China 500 B.C. Indigenous farmers used the cover crops as an alternative to allowing the field to remain fallow (leaving exposed soil between growing seasons) to improve soil conditions (Paine et al., 1993). The inclusion of winter annual cover crop species into a spring N management system has been proven to reduce the leaching potential and improve N use efficiencies (Ditsch and Alley 1993). Winter annual cover crop species have the capacity to absorb residual N, naturally mineralized N, and N added in the form of inorganic fertilizers, inhibiting loss via the three primary loss pathways (Thorup-Kristensen et al., 2003). After the N is assimilated within the biomass of the cover crop, it is then released back into the soil as it decomposes, becoming available to the subsequent crop. As previously stated, weather variability within the region directly influences the distribution of the NO_3^- within the soil profile. Therefore, it is crucial to have ground cover outside of the principal growing season to secure one of the producers' largest input costs (Doran et al., 1990).

The integration of cover crops into a conventional cropping system may serve to provide and conserve N for grain cash crops, reduce leaching potential, reduce soil erosion, reduce weed pressure, and increase soil organic matter content (Hartwig and Hoffman 1975). Although cover crops are a multi-faceted management tool, they are incorporated into cropping systems primarily to inhibit soil erosion (Romkens et al., 1990). Soil erosion is a process that can reduce the productivity of any agricultural field by removing the fertile topsoil. A cover crop stand physically reduces the amount of rainfall contacting the soil surface, preventing soil splashing and erosive surface runoff (Dabney, 1998). Another benefit of cover cropping that has increased integration into production systems is the potential for soil fertility management. The incorporation of certain cover crop species is being considered a viable option for producers needing to curb NO_3^- losses and increase overall N use efficacy (Sattell et al., 1999). Cover crops may have the ability to improve the use efficiency of an assortment of soil macro/micronutrients; however, out of the 17 essential nutrients, the focus has been placed on the impact of cover crops on conventional nitrogen management.

Cover crops have the ability to improve upon today's conventional management systems in regard to functionality. However, those functions challenge producers' ability to optimize their use within a given system. The capacity of cover crops to retain plant-available nitrogen can help to reduce the potential for N loading to surface waters; conversely, this complicates the timely release of nitrogen for crop growth (Danso et al., 1991).

Adoption. Formerly, the acceptance of cover cropping has been limited due to a lack of reception and use of contemporary farm type equipment, mainly the use of tillage practices (Paine et al., 1993). However, due to recent nationwide research efforts, the integration of cover cropping strategies into conventional production practices has been accelerated. According to a synopsis of crop producer surveys collected nationwide during the 2013-2014 cover cropping season by the conservation technology information center (CTIC), the average number of cover crop acres has risen per user, expanding from a mean of 80 acres in 2009 to an average of 207 acres in 2014. A recent trend of cover crop implementation has been observed in the 2012-2013 SARE-CTIC Cover Crop Survey; in the three years prior to that survey year, cover crop acreage had increased by an average of about 30% per year among cover crop users. Further projections of producers' 2014 acreage revealed an additional 10% increase in acres receiving some form cover crop. Of the total 2,903 respondents who answered the survey questions, 75% reported growing at least one species of cover crop in the past five years (Cover Crop Survey Report, 2013-2014). Based upon the surveyed producers, the MRB is the most densely cover cropped area in the continental United States. The greatest number of responses from producers implementing a cover cropping strategy were from Minnesota, Iowa, Missouri, Illinois, Indiana and Ohio, with 56 to 157 responses respectively (Cover Crop Survey Report, 2013-2014).

Impact on corn nitrogen uptake and grain yield. Implementing a winter annual cover crop to scavenge nutrients from an agricultural field after the harvest of a previous cash crop can effectively assist in the utilization of any residual N (Sattell et al., 1999). Mineralization of the cover crop residues in the spring have the ability to supply the subsequent crop with additional N to efficiently produce a high yielding grain, while sustaining ground cover and minimizing environmental degradation (Doran et al., 1990). Lotter et al., (2003) conducted a long-term field study in Pennsylvania documenting yield differences in organic versus conventional systems. Lotter found that when drought conditions are experienced, an organic corn-soybean crop rotation coupled with a cover crop would out-yield the conventionally produced crop grown without a cover crop present. Correspondingly, a Southern Coastal Plains regional study established three years of quantitative data involving N timing, rates and cover crop inclusion into a conservation tillage system. Reeves et al., (1993) reported based on multiple linear regression models, the maximum grain yields were obtained with a decreasing rate of application throughout the duration of the study. Also concluded from this study, split applications when coupled with a cover crop were deemed unnecessary due to the residual mineralization of the cover crop sustaining the late season crop needs (Reeves, 1993). The correlation between cover crop inclusion and corn grain yield within the Midwest is not well documented under a fall applied N management system.

Based upon the pool of knowledge in the literature, the inclusion of cover crops to improve the efficiency of N fertilizer in conventional row-crop agriculture is an emerging area of research. There is a dearth of knowledge in regard to the relationship between certain cover crop species and the efficacy of fall applied N at various application rates in a commercial practice. Therefore, the purpose of this study is to assess the effects of cover crops and alternate application rates in a row crop situation in order to improve the efficiency of the fall applied N management system.

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CHAPTER III

EFFICACY OF WINTER COVER CROPS TO IMPACT THE DISTRIBUTION OF SOIL INORGANIC N FOLLOWING FALL APPLIED ANHYDROUS AMMONIA

Abstract

The coupling of cover crops, along with spring application of nitrogen has shown improved nitrogen efficiency in corn production systems. However, studies have shown that only 50% of central Illinois farmers practice spring application of nitrogen. Therefore, the objective of this research was to determine the efficacy of winter cover crops to impact the distribution of soil inorganic N following fall applied anhydrous ammonium. The experimental site was located at the Illinois State University Research and Teaching Farm in Lexington, IL. The treatments consisted of a control, zero control and three cover crop treatments, daikon radish, cereal rye and a cereal rye/daikon radish mix. All treatments received a fall application of 200 kg N ha^{-1} in the form of anhydrous ammonia. Soil samples were collected in the spring at four separate depths and were analyzed for inorganic N. At the 0-5cm depth, we determined that tillage radish resulted in 18% greater soil NO_3^- relative to the control. In the environmental depth of 20-80cm, we observed that fall applying N into a living cover crop resulted in 35% (Cereal Rye) and 22% (Daikon Radish) less soil NO_3^- when compared to the control.

After four consecutive years of establishing a cover crop, corn uptake and yield data were collected. On average the addition of cereal rye and daikon radish treatments increased total crop uptake by 20% or 67.10 kg ha^{-1}. Consequently, sampling at harvest demonstrated the capacity of the monoculture cover crop species to increase the crop yielding potential by 6% or 0.8 Mg ha^{-1} relative to the control. Over a four year period, winter cover crops reduced nitrate leaching and stabilized a greater concentration of soil NO_3^- in the agronomic depths, relative to the control, following fall applied N. The results of this study also suggest that cover crop inclusion into a fall applied system has the potential to advance nitrogen use efficiency, yield and profitability.

Introduction

The application of nitrogen is essential to produce high yielding cropping systems necessary to meet the needs of the continually growing population. The manufacture of industrially fixed nitrogen (Haber-Bosch) is advantageous for corn production within the MRB (Wortmann et al., 2004). However, due to the excessive use of such products, agriculture is considered one of the major sources of N loading to surface waters. Randall and Vetsch conducted a 7 year study in Michigan to investigate the impact of N timing on nitrate leaching via subsurface flow. Similar annual N losses were documented when directly comparing fall versus spring N management strategies (Randall et al., 2003). However, in a year (1999) with abnormally high temperature and precipitation values, spring application increased corn yield by 25% and reduced NO_3-N loss compared with fall application across four various tillage systems (Vetsch and Randall, 2004). The results from that study determined that spring N application reduced NO_3-N leaching by 14% compared to fall (Randall and Vetsch 2005). Despite N loss potential and decreased corn yield, in some areas of the MRB approximately 50% of the nitrogen fertilizer is still applied in the fall (Smiciklas et al., 2008).

The connection between nitrate loss from agriculture fields and the eutrophication (hypoxia) in the Gulf of Mexico has become inherently clear (Alexander et al., 2000). According to Goolsby the amount of nitrate loading delivered to the Gulf of Mexico has nearly tripled since the 1950's (Goolsby et al., 1999). The Mississippi River annually transports 1.57 million metric tons of NO_3^- to the Gulf of Mexico. Multiple studies approximate up to 81% of the total nitrogen flux are a derivative of agriculture. Leachate as subsurface flow and runoff as overland flow have been directly linked to 63% of the total, while atmospheric deposition (deposition of nitrous oxides from continuous consumption of fossil fuels) contributes about 18% of the 1.57 million metric tons (Alexander et al., 2000). Traditional cultural practices that followed the general precedent of applying extra units of N based upon given field historical yield levels will no longer be economically feasible, nor will it be acceptable to obtain new environmental objectives set by the EPA (Camberato, 2012).

The integration of cover crops into a conventional cropping system may serve to provide and conserve N for grain cash crops and reduce leaching potential. The inclusion of winter annual cover crop species into a spring N management system has been proven to reduce the leaching potential and improve N use efficiencies (Ditsch and Alley, 1993). Winter annual cover crop species have the capacity to absorb residual N, naturally mineralized N, and N added in the form of inorganic fertilizers, inhibiting loss via the three primary loss pathways (Thorup-Kristensen et al., 2003). McCracken et al., (1994) observed that cereal rye demonstrated the ability to hold nitrate concentrations at nearly zero kg N L^{-1} over the fall, winter and early spring.

In addition to NO_3-N reduction potential; studies have shown that cover crops can improve overall N use efficiency and subsequent crop grain yields. Lotter et al., (2003) conducted a long-term field study in Pennsylvania documenting yield differences in organic versus conventional systems. Lotter found that when drought conditions are experienced, an organic corn-soybean crop rotation coupled with a cover crop would out-yield the conventionally produced crop grown without a cover crop present. Reeves et al., (1993) reported based on multiple linear regression models, the maximum grain yields were obtained with a decreasing rate of application throughout the duration of the study. The correlation between cover crop inclusion and corn grain yield within the Midwest is not well documented under a fall applied N management system. There is a dearth of knowledge in regard to the relationship between certain cover crop species and the efficacy of fall applied N in a commercial practice.

Therefore the objectives of this study are to (i) quantify the N uptake capacity of cereal rye, daikon radish and a cereal rye/daikon radish mixture to sequester residual and fall applied nitrogen (ii) evaluate the ability of different cover crops to reduce nitrate leaching following the fall N application (iii) determine the capacity of different cover crops to impact subsequent cash crop uptake and yield. This study will allow for the assessment of the impact of different cover crop species on nitrate leaching and fall grain yields following fall N application into a living stand of cover crops.

Materials and Methods

The experimental site was located at the Illinois State University agriculture research farm in Lexington, Illinois. The predominant soil type that exists within the study site is Drummer El Paso silty clay loam. This soil type is poorly drained, and contains a slope of 0-2%. The cropping history of the field has been continuous corn (*Zea mays L.*) for the last 8 years to support silage production, and converted to a commercially harvested grain practice at the end of the 2013 growing season. The experimental location (54.88 m. in width east to west, 129.57 m. in length north to south), was divided into a total of 21 (.5 acre, .202 ha) plots. The research site was arranged in a complete randomized block design; with three replications of each treatment. The N rate chosen for this study was the suggested MRTN (Maximum return to Nitrogen) of 200 kg N ha^{-1}for central Illinois developed by the N rate calculator (Iowa State University).

Research variables:

- Nitrogen application rate (200 kg ha^{-1}).
- Treatments- control (no cover crops), daikon radish (*Raphanus sativus L.*), cereal rye (*Secale cereal L.*) and a daikon radish/ cereal rye blend.

These independent variables were designated to determine the effects of cover crops on the distribution of inorganic N within the soil profile prior to cash crop planting. Also observed was the capacity of the cover crop to impact the total N uptake at critical growth stages and overall grain yield (dependent variables).

Cultural Practices

For application purposes, the study followed major agricultural practices within the MRB. Application dates were based on an annual basis due to in-season weather variability. An early maturity corn hybrid (2,620 Growing Degree Days, GDD) was planted in the month of May (2014 and 2015) with a 12 row John Deere planter at 85,250 seeds per hectare. The row spacing used was 76.2 cm, which is the predominant spacing used within the region. In-season weed control was achieved with a Glyphosate herbicide application before the corn reached the eighth vegetative stage (V8). In September (2014-2015) the crop was commercially harvested once it reached maturity; moisture at harvest was 20%. After harvest was completed, the cover crop treatments were drilled into existing crop residue from conventional harvesting practices. The cover crop seeding rates used were developed by the sustainable agriculture research and education program.

Table 1

Cover Crop Seeding Rates

Cover Crop Species	Land Area (Hectare)	Seeding Rate (kg/ha^{-1})	Kg. Seed needed
Cereal Rye	0.61	67.2	41.0
Daikon Radish	0.61	6.70	4.10
Cereal Rye (85%)/Daikon Radish (15%)	0.61	56.1	84.1

Note. Data gathered from the Sustainable Agriculture Research and Education Program (2015)

The application of nitrogen occurred once the average daily soil temperature fell below 10°C. The N source was applied directly into a living stand of cover crops in the form of anhydrous ammonia prior to the primary crop growing seasons (Figure 1).

Figure 1. Fall application of anhydrous ammonia into a living cover crop stand

Throughout the duration of the study, daikon radish plants winter terminated in December from subfreezing temperatures and vegetative desiccation. In the spring, chemical termination of the cereal rye was accomplished using a non-selective herbicide (Glyphosate and 2, 4-Dichlorophenoxyacetic acid) to eradicate the cover crop stand approximately two weeks before the anticipated planting of the cash crop. Seedbed preparation prior to corn planting was achieved with a soil finisher upon the complete necrosis of the cover crop.

Plant Sampling

Representative cover crop samples were obtained using a random selection process. Within each treatment, four 0.6858 m^2 quadrants were collected to create a composite cover crop sample. This sampling technique was modified from a method developed by Dean and Weil in 2009. Cover crop growth was documented and sampled in both the fall and spring seasons. The above ground biomass was sampled within each of the cover crop treatments; no samples were collected from either the control or zero control. All of the samples were oven dried at 60ºC, weighed and ground to pass through a 1-mm. sieve. Total percent nitrogen determination is achieved using a dry combustion method; a 0.1000 g. sample was analyzed via LECO FP-528 N Analyzer. Dry weight of each sampling quadrant was quantified and used to determine overall biomass and total nitrogen uptake. Nitrogen uptake was calculated by multiplying %N by total biomass (kg ha^{-1}). Growing degree days (GDD) were calculated for each growing season, to correlate cover crop biomass and N uptake with trends observed in soil distribution and subsequent crop uptake and yield. To calculate GDD, a base of 0°C was used; the calculation for winter annual crops was derived from Montana State University (Miller et al., 2001).

Cash crop samples were taken at critical development stages throughout the growing season. The growth stages and sampling points that were considered critical are based upon previously conducted research involving nutrient uptake and total N (V6, V12, VT and R6). Population density was conducted twice within each treatment in a random fashion during each critical growth stage sampling. One one-thousandth of an acre was represented using a 5.334 m constant, from this measurement two whole plant samples from each treatment were procured and analyzed collectively. Reproductive growth stage samples were further divided into sample subsets (grain, cob, lower stalk, and the remainder of the plant). Corn grain yield and moisture content data were analyzed after the completion of each harvest season. Yield was calculated using weights collected from a verified weigh wagon, those weights were then corroborated by the local grain cooperative. The samples were oven dried at 60ºC, weighed and ground to pass through a 1-mm sieve. Total percent nitrogen determination is achieved using a dry combustion method; a 0.1000 g sample was analyzed via LECO FP-528 N Analyzer. Total N data was used to establish nitrogen uptake for each treatment. Nitrogen uptake was calculated by multiplying %N by total biomass (kg ha^{-1}).

Soil Sampling

Soil samples were taken both in the spring prior to the cash crop growing season and in the fall post-harvest to document the effect of cover crops on inorganic N distribution. To properly depict the distribution of N within the profile, the samples were collected to a depth of 80 cm. Two soil cores were randomly collected within each treatment using a hydraulically driven probe. The soil cores were subdivided into four sections of 0-5, 5-20, 20-50, and 50-80 cm. The 0-5 and 5-20 cm cores were designated the agronomic depth (rooting zone), and the 20-50 and 50-80 cm cores were labeled as the environmental depth (below the rooting zone and near pattern tile drainage). The soil samples were oven dried at 60ºC, and ground to pass through a 1-mm sieve for analysis. A five gram sample was shaken with 50 ml of a 0.01 M $CaCl_2$ solution for 30 minutes to allow for proper amalgamation. The mixture was then separated at 1500 RPM using centrifugal force; after adequate separation the solution was filtered using Whatman #42 filter paper and analyzed using LACHAT flow injection analysis auto sampler calorimetrically. Total soil inorganic nitrogen was determined for each depth using a bulk density of 1.21g cm^{-3}. All procedures and instrumentation used for the duration of this study are widely accepted and documented means of data analysis within the scientific community.

Statistical Analysis

The research formatting used for the duration of this study was a complete randomized block (CRB) design with three replications. Statistical analysis of NO_3-N and

NH_4-N concentrations across depth (CRB design), cover crop N uptake and biomass were conducted using ANOVA as calculated by SAS PROC general linear model (GLM). Crop N uptake and yield analysis was conducted using CRB modeled ANOVA as calculated by PROC GLM. Cover crop treatments were considered fixed effects, while block was treated as a random variable. REGWQ (Ryan-Einot-Gabriel-Welsch Q test) comparisons test was used to compare treatments to each other and to the control. Orthogonal contrast was used to determine yield significance between treatments and application rates. A P level of <0.05 was used to determine significant differences between treatments.

Results and Discussions

Environmental Conditions

The average annual ambient air temperatures for 2011-2015 were 10.7, 12.6, 10.0, 8.7 and 10.6°C, respectively (Fig. A-1). The mean temperature for those years were comparable to the 30 year average of 10.8°C; however, the variance on a monthly basis was considerably greater. Ambient air temperature in 2011 followed the general weather patterns of the 30 year average; however, the mean monthly temperature for the first 6 months were below the 30 years values. Warmer ambient monthly temperatures did not occur until the months of October, November and December 1.0, 2.0 and 3.4°C warmer than the 30 year average, respectively. These warmer temperatures trended into the 2012 season until the month of April. Average monthly ambient air temperatures in 2012 were significantly warmer than the 30 year average with January, February, March, April, May and December 3.0, 2.9, 8.3, 1.0, 2.5 and 4.0°C warmer relative to the 30 year average, respectively. In contrast, the 2013 season generated below average ambient air temperatures for February, March, April, June, July, August, November and December 0.6, 4.2, 1.6, 0.4, 1.2, 0.5, 2.1, 1.9°C lower than the 30 year regional average, respectively.

Annual precipitation totals in 2011 and 2013 were greater than the 30 year average; however in 2012, rainfall values were substantially below the regional values (Fig. A-2). Annual precipitation in 2011 was 95.3 mm greater than the 30 year average; all monthly rainfall totals were above average with the exception of August, September and October. Annual precipitation in 2012 was 212.3 mm less than the 30 year average; the months of January, February, March, April, May, June, July, November and December registered precipitation values 21.5, 18.6, 42.3, 20.3, 53.9, 57.6, 61.2, 52.8 and 9.3 mm below average, respectively. Annual precipitation in 2013 was greater than the 30 year average; the months of January, February, April, May and October had 332.1, 83.0, 35.8, 63.1, and 7.1 mm greater precipitation compared to the 30 year average for the region, respectively.

In 2014, the average ambient air temperatures were considerably below the aforementioned 30 year average temperature. Annually, 2014 was 2.1 ˚C cooler than the 30 year average. The lowest recorded temperatures observed throughout the duration of the study were in the months of January and February 2014, -8.9 and -9.0 ˚C; 5.1 and 6.9 ˚C lower than the regional average, respectively. However, the months to follow were consistent with the 30 year values. April-October recorded average temperatures within 1°C of the average regional temperature.

Annual precipitation in 2014 was 166.9 mm below the 30 year average of 972.8 mm. However, during the cash crop (corn) growing season, the average rainfall total was similar to the 30 year average. The total precipitation received throughout the months of May-September, was 3.6 mm less than the regional average.

Ambient air temperatures in 2015 followed the general trends that were observed during the initial year of the study in 2011. The average temperature in 2015 was 10.6°C, which was only 0.1°C lower than the recorded average temperature in 2011. Both years were comparable to the 30 year average temperature. However, during the late winter and early spring months in 2015, the ambient air temperatures were significantly cooler than the 30 year average with January, February and March -0.8, -6.1 and -1.9°C cooler relative to the 30 year average, respectively.

In 2015, annual precipitation totals were approximately 1,057 mm, thus receiving 84 mm more than the 30 year regional average. This year marked the second highest precipitation total throughout the duration of the study, second only to 2011, which recorded 1,068 mm of total precipitation. The largest concentration of total precipitation came in the form of rainfall during the summer months, May, June, July and August receiving 23.5, 78.5, 40.9 and 9.9 mm more than the regional 30 year averages, respectively. Ensuing average rainfall values in the fall, the winter months of November and December recorded uncharacteristically warm temperatures. This temperature flux supplemented large amounts of rainfall that are atypical for the region. In the months of November and December, 251.7 mm of total precipitation was recorded, 112.9 mm greater than the regional average.

Cover Crop Nitrogen Uptake and Biomass Production

The various weather patterns experienced throughout the 2011-2015 cover crop seasons (September-March/April) allowed for data collection to occur under diverse growing conditions. Under these conditions, cover crop performance was evaluated for biomass production and N sequestration potential. For the intended purposes of this study, the N scavenging ability of the aforementioned cover crop treatments were documented to determine capacity to stabilize fall applied N.

Sampling the cover crop in both the fall and spring throughout the growing season for four consecutive years (2011-2015), resulted in a significant interaction between year sampled and cover crop species for both biomass and total N uptake (Table A-5) (Table A-6). In the 2011-2012 cover crop growing season, 2547 growing degree days (GDD) were experienced (Table A-2); this being the most accumulated in one growing season throughout the duration of the study. Due to seasonally warm winter months experienced during the cover crop growing season, (November, December and January 2.0, 3.4 and 3.0°C warmer than regional 30 year averages) senescence of the daikon radish was not achieved until early January. In conjunction with abnormally high ambient air temperatures, precipitation values were also greater than the regional average. During that seven month timeframe, 396 mm of total precipitation occurred, 171 mm of that total occurred December-March succeeding the application of anhydrous ammonia in November. Thus, allowing for the possibility of early nitrification to occur, resulting in high biomass and N uptake values for the various treatments due to greater plant available nitrogen. During the 2011-2012 growing season, the daikon radish treatment accumulated 6561.9 kg ha^{-1} dry matter and absorbed 226.8 kg N ha^{-1}. Relative to daikon radish, the cereal rye treatment accumulated significantly less (3906.5 kg ha^{-1}) dry matter, while the total N uptake (188.1 kg N ha^{-1}) was less, the difference was insignificant (Table A-3) (Table A-4). The cereal rye/daikon radish mixture in 2011-2012 produced the least amount of (2363.7 kg ha^{-1}) dry matter and total N (110.6 kg N ha^{-1}). The reduction in biomass observed for the mixture in comparison to either the daikon radish and cereal rye treatments was significant, while the reduction in uptake was only significant relative to the daikon radish treatment.

In contrast to the previous season, the 2012-2013 cover crop growing season (September 2012-April 2013) had below average monthly temperatures with the exception of December and January. Below average temperatures that occurred throughout the growing season reduced the total GDD experienced (1845) (Table A-2). Despite reduced GDD, substantial early fall precipitation created conditions conducive for residual soil N to be assimilated within the cover crop biomass prior to the ambient air temperature reaching the 0°C threshold for cover crop growth to continue. However, in 2012-2013, we observed a significant reduction in both daikon radish biomass (3707.5 kg ha^{-1}) and total N uptake (131.9 kg N ha^{-1}) relative to the previous growing season (Table A-3) (Table A-4). Conversely, due to rigorous spring growth, a later termination date and a large quantity of residual N remaining from the 2012 drought (May-July), biomass production was equivalent to the previous growing season for both cereal rye and the mixture. However, in comparison to the previous year, the 2012-2013 cereal rye produced significantly a greater total N concentration (249.9 kg N ha^{-1}). Coinciding with an annual increase relative to the previous growing season, cereal rye demonstrated the ability to significantly increase the total N concentration and biomass production in comparison to daikon radish treatment. In 2012-2013, the increase in cereal rye biomass production and total N concentration relative to the daikon radish could be attributed to limited fall GDD. Similarly the mixture also demonstrated the capacity to increase the cover crop N uptake (128.1 kg N ha^{-1}) in 2012-2013, however, the difference was insignificant. Diminished fall growth potential demonstrated how temperature deficit is more influential on the daikon radish treatments. This was evident because the cereal rye treatment and the mixture; which was seeded at 85% cereal rye, both experienced spring growth and recorded an increase in N uptake and biomass totals relative to the previous year.

The 2013-2014 cover crop growing season displayed cooler ambient air temperatures, with January (-8.9 °C) and February (-9.0 °C) being the coldest months on record throughout the duration of the study. The below average regional temperatures effectively condensed the growing season in comparison with the previous two growing seasons, with a total of 1679 GDD accumulated during the months of September-April (Table A-2). Annual anhydrous ammonia application occurred mid-December; however, minimal N was assimilated within the cover crop biomass due to the abnormally cold temperatures and low precipitation. Due to these environmental conditions, both cover crop biomass production and total N uptake data yielded significantly less for all treatments in comparison to the previous two seasons (Table A-3) (Table A-4). Early senescence of the daikon radish led to a significant reduction in biomass production (1450.3 kg ha^{-1}) and N uptake (38.2 kg N ha^{-1}). Cereal rye dry matter accumulation (706.8 kg ha^{-1}) and total N uptake (35.1 kg N ha^{-1}) in 2013-2014 were significantly limited by weather patterns in both the fall and spring. The cereal rye/daikon radish mixture had significantly less dry matter (670.2 kg ha^{-1}), while N uptake (32.5 kg N ha^{-1}) was similar to the previous season. Minimal biomass production and an early dormancy period for the cereal rye and the mixture reduced uptake potential in the fall. Due to cold spring ambient air temperatures, cereal rye development was restricted, which reduced the total amount of GDD received and limited spring uptake potential.

Directly ensuing 2014 grain harvest was the fourth consecutive year of cover crop establishment (2014-2015). Due to a productive corn crop, little residual N remained after harvest. Rather than succeeding silage, the cover crop was sewn directly into a dense corn residue. Monthly ambient temperatures during the growing season (September-April) were again well below 30 year regional averages. Similar to the previous growing season, seasonally colder temperatures limited the quantity of GDD accumulated in the fall (Table A-2). With the fewest fall GDD accumulated, minimal N available for uptake, and dense residual ground cover, the daikon radish biomass production (638.39 kg ha^{-1}) totaled a significant 66% reduction relative to 2013-2014, while N uptake values (31.90 kg ha^{-1}) were maintained in comparison to the previous season (Table A-3) (Table A-4). Relative to the previous spring seasons, 2015 accumulated the highest GDD total (649). As a result, the 2014-2015 season allowed for exponential spring growth of cereal rye; which, significantly increased both biomass production (2159.9 kg ha^{-1}) and N uptake (107.2 kg N ha^{-1}). Though insignificant, the mixture emulated the cereal rye and demonstrated an increase in both biomass (978.3 kg ha^{-1}) and total N uptake (52.3 kg N ha^{-1}).

In order to recognize the trends that occurred, the collective data were averaged for each treatment over the duration of the four year study. This allowed direct comparison of the average biomass production and total N concentrations for each treatment. Sampling the cover crop in the fall and again in the spring two weeks before termination, resulted in a significant difference in both total uptake and biomass production between cover crop treatments. We observed above ground biomass production (2011-2015) for the monoculture cover crop species, cereal rye and daikon radish averaged 3089.7 and 3089.5 kg ha^{-1}, respectively. In comparison to studies conducted by Kasper and Bakker 2015, cereal rye biomass production over a four year period (2006-2009) averaged 1894 kg ha^{-1}. While a Dean and Weil (2009) study recorded daikon radish dry matter totals over a two year period (2003-2004) at multiple locations, which averaged 3796 kg ha^{-1}. Although both monocultures produced similar biomass over the extent of four year and in comparison to other studies, the cereal rye/daikon radish mixture averaged significantly less biomass (1840.2 kg ha^{-1}) throughout the duration of the study (Table A-3). Due to weather conditions experienced over the four year period, N uptake ranges for daikon radish, cereal rye and the mixture were 32-226 kg ha^{-1}, 35-250 kg ha^{-1} and 32-128 kg ha^{-1}, respectively. According to cited literature, in a spring applied system (Dean and Weil, 2009; Kasper et al., 2007; Strock et al., 2004) cover crop total N uptake ranged from 100-119 kg N ha^{-1} and 42-78 kg N ha^{-1} for daikon radish and cereal rye, respectively. Within our study, cereal rye demonstrated the ability to sequester the highest N concentration in comparison to daikon radish and the mixture (Table A-4). In 2011-2015, cereal rye, daikon radish and the mixture averaged N uptake values of 145.1, 107.2 and 80.9 kg N ha^{-1}, respectively. The data demonstrated the ability of the cereal rye to sequester a significantly greater N concentration than both the daikon radish and cereal rye/daikon radish treatments. While significantly less in comparison to the cereal rye treatment, the daikon radish treatment was able to significantly increase total N concentrations within the cover crop biomass, relative to the mixture. Thus, the data suggests that on an annual basis, these cover crop species have to ability to absorb

15-100% of the fall N in the Upper Mississippi River Basin, assuming a range of N rates applied (200-224 kg ha^{-1}).

Long-Term Cover Cropping Effects on Spring Soil Nitrogen Distribution

In order to measure how long-term cover crop integration influences spring soil N distribution following a fall N application, soil samples were taken 1-3 weeks prior to planting. The precedent for selecting soil sampling dates prior to planting was based upon the Illinois Agronomy Handbook's suggested planting dates for North and Central Illinois (April 16th) (Nafziger, 2003). To quantify the data, the soil profile (0-80cm) was studied in its entirety; however two principal regions of focus were formed; the agronomic depth (0-20cm, zone of root interception and depth of anhydrous ammonia application) and the environmental depth (20-80cm; the portion of the soil profile that is most susceptible to tile-drainage losses).

In 2012 following the application of fall anhydrous ammonia, 177mm of precipitation occurred in the months of December-March. In conjunction with the precipitation, above average ambient temperatures resulted in a prolonged cover crop growth period (2547 GDD) with soil temperatures above the 0°C cover crop growth threshold (Table A-2). These conditions were conducive for mineralization of any organic residue and subsequent nitrification of NH_4-N. As a result, in 2012, three weeks prior to planting we observed greater soil NO_3-N for the control treatment relative to all cover crop species. Conventional fall N application without cover crops (Control) resulted in a NO_3-N content of 274.6 kg ha^{-1} within the entire soil profile (Fig. A-3). While the cereal rye, daikon radish and the mixture recorded comparable cumulative NO_3-N concentrations of 135.9, 180.4 and 170.2 kg ha^{-1}, respectively. Despite depth, in early spring of 2012, fall applying N directly into a living cover crop stand reduced soil NO_3-N within the entire 0-80cm depth by a range of 94.2 -138.7 kg ha^{-1}, however, this difference was found to be insignificant for all treatments except for cereal rye (Fig. A-4). Although there were minimal statistical differences between treatment and year, there were major biological differences that correlated with variance found when averaged across depth (0-80cm). In 2012, the daikon radish winter killed in January, allowing for three months of decomposition to occur. In conjunction with winter senescence, a lower C: N ratio could have attributed to similar NO_3-N values relative to the control. However, at the point of the spring soil sampling, a percentage of the scavenged N remained within the organic form as plant residue. This is significant because plant available nitrogen (PAN) at the agronomic depth has the potential to increase as the cover crop residue continues to mineralize. Within the control treatments, where there is no cover crop residue, the potential for inorganic N to increase is minimal. Relative to daikon radish, the cereal rye cover crop overwintered and continued to sequester N until chemically terminated in the spring. Consequently, a higher percentage of the fall applied N was absorbed and assimilated into the cover crop biomass. This translated into a 46% lower NO_3-N concentration for the cereal rye and the mixture in comparison to the control within the agronomic depth (Fig. A-3). While, the addition of daikon radish and the mixture also increased NH_4-N concentrations within the agronomic depth by an average of 15% (Fig. A-5). Despite the environmental conditions following the application of fall anhydrous, the integration of cover crop treatments into conventional MRB practices substantially reduced the concentration of soil NO_3-N within the environmental soil depth (20-80cm). This reduction can be attributed to capacity of the cover crop to sequester and assimilate fall applied N, preventing loss via leaching. Spring NO_3-N concentrations within 20-80cm profile in 2012 were on average 45% greater for the control relative to when N was fall applied into a standing cover crop. Similar results were observed by Adeli et al., 2001, where broiler litter was fall applied directly into the cereal rye stand, which resulted in a 57% decrease in NO_3-N leaching at a depth of 60cm with cover crops relative to non-cover crop treatments. The 2012 data demonstrates the ability of the cover crop to influence the distribution of soil inorganic N, reducing its vulnerability to leaching under various conditions.

Following the drought experienced during the 2012 cropping season, excess residual nitrogen remained within the soil profile. However, the 2013 cover crop season was trended by an uncharacteristically high volume of rainfall; within the months of January to March, the total precipitation was twice the amount received in 2012. As a result of the environmental conditions, the 2013 cover crop growing season was effectively reduced by 702 GDD relative to previous season (Table A-2). The substantial precipitation received after the application of anhydrous ammonia expedited spring NO_3-N leaching, which was evident within the spring soil sample data. The average NO_3-N concentrations increased with depth; The 20cm (37.5 kg ha^{-1}) depth resulted in a significantly lower concentration than both the 50cm (57.8 kg ha^{-1}) (Ryan-Einot-Gabriel-Welsch Multiple Range Test (REGWQ), df= 30, $P < 0.0001$) and 80cm (60.7 kg ha^{-1}) (REGWQ, df= 30, $P < 0.0001$) depths (Fig. A-6). Within the entire soil profile, cereal rye (98.0 kg ha^{-1}) and the control (160.0 kg ha^{-1}) displayed a significantly reduced NO_3-N concentration in comparison to daikon radish (199.4 kg ha^{-1}) and the mixture (217.3 kg ha^{-1}) (Fig. A-7). The presence of daikon radish in either the mixture or monoculture form demonstrated the ability to increase the overall NO_3-N (0-80cm) concentration prior to planting in comparison to the control. However, relative to the control, a significant portion of the NO_3-N was assimilated within the cereal rye residue; thus preventing loss via leaching and denitrification, to be slowly returned throughout the growing season as the cover crop residue decomposes. This increase in inorganic N for the daikon radish could be related to environmental conditions experienced during the cover crop growing season, which caused winter senescence of the daikon radish to occur in early December. Therefore decomposition of the daikon radish residue was possible during the winter months, the additional NO_3-N was contributed via mineralization. Berg and McClaugherty, 2007 verified that increasing soil N concentrations within a cover crop treatment can be attributed to litter mass (above ground biomass) lost or decomposed, resulting in a linear increase until the limit value for decomposition has been reached. The total observed NO_3-N concentrations within the soil profile for daikon radish (199.4 kg ha^{-1}) and the mixture (217.3 kg ha^{-1}), were greater than the rate of ammonia application (200 kg ha^{-1}). Conversely, both the daikon radish and daikon radish/cereal rye treatments were unsuccessful in reducing the total NO_3-N content that reached the environmental depth in comparison to cereal rye. This trend was also observed in a study conducted in Maryland (Dean and Weil, 2009) that associated the daikon radish decomposition period to increased NO_3-N on course textured soils at lower depths. In contrast, cereal rye yielded substantially less NO_3-N at the agronomic depth, possibly attributed to immense spring growth where a significant portion of the potentially available N was assimilated within the residue. Despite a wet spring in 2013, fall applying N into a living stand of cereal rye also demonstrated the capacity to reduce the concentration of soil NO_3-N by 46% within the environmental soil depth. This is a substantial observation considering the percentage of farmers that fall apply N, which ranges from 25-75% within some regions of the MRB (Randal and Sawyer, 2005; Smiciklas et al., 20008; Lemeke et al., 2010; Bierman et al., 2012).

Following a productive silage crop in 2013, nominal residual nitrogen pools were unable to produce sufficient cover crop growth. The 2014 cover crop season was trended by exceedingly cold temperatures within the months of January to March, with average temperatures 6°C below the 30 year regional average. Lower seasonal ambient air temperatures limited GDD accumulation to 1679 (September-April) (Table A-2). Due to the lower temperatures experienced in the fall, early December senescence of the daikon radish occurred. Subsequent cool spring temperatures potentially reduced cover crop mineralization and subsequent soil nitrification, which would have increased total N retention at the upper depths and minimized leaching potential. Therefore, at the point of spring soil sampling, minimal N movement had occurred and a significant portion of the scavenged N remained within the organic form as plant residue. On average, the 2014 NO_3-N concentrations were some of the lowest recorded for all depths throughout the four year duration. Relative to the two previous years, 2014 documented significantly less NO_3-N at both the 20cm (REGWQ, df= 30, P= 0.0462) and 80cm (REGWQ, df= 30, P= 0.0083) depths, respectively (Fig. A-9). Despite a limited N pool, the presence of cereal rye (109.2 kg ha^{-1}), daikon radish (92.0 kg ha^{-1}) and the mixture (66.5 kg ha^{-1}) considerably reduced soil NO_3-N by a range of 15- 48% (Fig. A-10). This difference was found only to be significant relative to the cereal rye/daikon radish mixture. At the upper depth both daikon radish and the mixture documented the lowest NO_3-N concentrations;

this was a trend only observed in 2014. One possible explanation for this deficit is that a component of N was undetected, sampling the above ground cover crop biomass only depicts approximately 50% of total uptake. According to Sundermeier 2008, dry matter accumulation is a 1:1 ratio for above ground/below ground biomass. Another justification would be that the daikon radish and the daikon radish/cereal rye treatments experienced a greater percentage of the total nitrogen at the agronomic depth being denitrified due to location within the field, as the majority of the total N was in the form of NO_3-N. Despite weather patterns limiting cover crop uptake, at the environmental depth, a reduction in NO_3-N was observed wherever a cover crop treatment was present. Both daikon radish and the mixture on average reduced NO_3-N concentrations at the lower depths by 21%, while cereal rye remained comparable to the control treatment.

In September of 2014, the first harvest of corn as a grain crop rather than silage was completed. Events of precipitation were frequent and ambient air temperature were comparable to the regional 30 year average. Grain production in the 2014 season established comparatively high yields for McLean County and the surrounding areas. Directly ensuing harvest was the establishment of the cover crop treatments. Due to minimal precipitation and deficient ambient temperatures experienced in the fall (Late September- Early December), winter senescence of the daikon radish was achieved in December. Consequently, daikon radish N sequestration capacity was limited relative to the previous years. However, due to warmer ambient temperatures in the spring of 2015, cereal rye spring growth was exponential having accumulated 649 GDD (spring total), relative to 443 GDD in 2014 (Table A-2). Therefore a greater percentage of scavenged fall applied N was assimilated within the cereal rye residue and the average soil NO_3-N was less relative to daikon radish and the mixture. Despite warmer spring temperatures, the inorganic N remained within the zone of fertilizer application. The 20cm (74.5 kg ha^{-1}) depth recorded the largest NO_3-N content at this depth over the four year period (Fig. A-12). In the spring of 2015, two weeks prior to planting, we observed no significant differences between cover crops and control treatments (Fig. A-13). However, there was a general trend for cereal rye (105.8 kg ha^{-1}) to have less soil NO_3-N relative to the control, while both daikon radish (178.8 kg ha^{-1}) and the mixture (141.3 kg ha^{-1}) increased NO_3-N values within the profile relative to the control (126.0 kg ha^{-1}). At the agronomic depth, fall applying N directly into a living stand of cereal rye reduced the overall soil NO_3-N by 21% and increased the concentration of NH_4-N by 38%. Relative to control, at the agronomic depth, the presence of daikon radish in either form (monoculture or mixture) exhibited an average increase of 28 and 79% in NO_3-N and NH_4-N content, respectively. This increase in total inorganic N could potentially be attribute to a lower C: N ratio and spring temperatures that facilitated prompt mineralization and subsequent nitrification. However, both the daikon radish and daikon radish/cereal rye treatments were unsuccessful in reducing the total NO_3-N concentration within the environmental depth relative to the control. In contrast, the cereal rye treatment continued to decrease mobile N by 8% within the environmental depth relative to the control, despite environmental conditions which prevented the movement of soil N.

In order to recognize the general trends that occurred, we averaged the collective data for each treatment over the duration of the four year study. This allowed us to directly compare the percentage of total NO_3-N and NH_4-N that was distributed within the agronomic and environmental depths of the cover crop treatments comparative to the control. The cereal rye treatment demonstrated the greatest capacity to influence N distribution over the four year period. At the agronomic depth, cereal rye on average reduced soil NO_3-N by 34% and increased the NH_4-N concentration by 17% in comparison to the control. Relative to the control, cereal rye reduced NO_3-N content by 35% at the environmental depths. The daikon radish/cereal rye mixture exhibited the ability to influence N in a similar manner as cereal rye; however, the percent reduction was not as noteworthy. Daikon radish demonstrated the capacity to increase both NO_3-N by 18% and NH_4-N on average by 52% within the agronomic depth. Fall applying N directly into daikon radish residue resulted in a 22% reduction of total soil NO_3-N within the 20-80cm portion of the soil profile relative to the control.

Cover Cropping Effects on Corn Nitrogen Uptake

In order to quantify the long term effects of cover cropping on a conventional crop production system, corn N uptake (Total N) was measured throughout the 2014 and 2015 corn growing seasons at critical growth stages. The corn biomass and uptake sample data, in conjunction with yield data aided in determining how the corn crop reacts throughout the growing season when introduced into a long-term cover crop management system.

In 2014, the environmental conditions following spring soil samples (April-June) emulated the 30 year regional values; the ambient air temperature was 0.1°C cooler, while total precipitation received was 13.7 mm greater. These conditions were conducive for soil mineralization and nitrification, with a sufficient nutrient supply available in the soil solution early season (V6) crop samples were able to sequester a range of 8-14% of the total uptake by the sixth vegetative stage (Fig. A-18). The presence of cereal rye in either in the monoculture or mixture slightly reduced the total N content in comparison to control (39.90 kg ha^{-1}). However, the daikon radish treatment (43.56 kg ha^{-1}) demonstrated the ability to sequester on average the highest N concentration at V6 relative to the control (39.90 kg ha^{-1}), cereal rye (31.64 kg ha^{-1}) and the cereal rye/daikon radish mixture (29.15 kg ha^{-1}), respectively. Though this difference was insignificant, this slight decrease at V6 for cereal rye, could potentially be attributed colder winter temperatures, which limited early season mineralization and increased N retention within the cover crop biomass. Therefore, the available source of N that was applied as an inorganic fertilizer in the fall was sufficient for the corn crop to have reached its total N uptake capacity.

Subsequent to V6 samples, the weather conditions in the months of June and early July were similar to the 30 year regional averages; growing conditions continued to be ideal for natural soil processes. The second and third crop samples were taken one week apart from one another. Both V12 and VT samples were collected in the second-third week in July. On average at V12, the addition of a cover crop increased the total N content by 20% or 33.0 kg ha^{-1} relative to no cover crop control. The cereal rye (187.12 kg ha^{-1}) demonstrated the ability to sequester on average the highest N concentration at V12 relative to the cereal rye/daikon radish mixture (159.47 kg ha^{-1}), daikon radish (156.70 kg ha^{-1}) and control (134.78 kg ha^{-1}) (Fig. A-18). As a result of the added cover crop in 2014, the corn crop was able to sequester a range of 50-58% of the total uptake by the twelfth vegetative stage, in comparison to the control which accumulated only 47% of the total uptake by this growth stage. The twelfth vegetative growth stage was the first documented stage where the addition of a cover crop made a biological impact on the total N concentration within the crop biomass. Until this sampling point, the applied fertilizer was sufficient in supplying the crop with the necessary nutrients. Relative to V6, the mid-season growth stages potentially utilized mineralized N from the cover crop to help supplement the limiting N source. Weather conditions experienced through VT were conducive for crop growth, but the regularly saturated soil conditions potentially could have advanced leaching and denitrification processes. At VT the addition of either monoculture cover crop species increased crop uptake by 16% or 33.5 kg ha^{-1}, however no statistical differences were observed (Fig. A-18). At tassel, the cereal rye/daikon radish (177.22 kg ha^{-1}) and the control (178.09 kg ha^{-1}) treatments yielded lower total N uptake values in comparison to the cereal rye (213.28 kg ha^{-1}) and daikon radish (209.90 kg ha^{-1}) treatments, respectively.

The ambient air temperature throughout the remainder of the growing season remained consistent with the regional average values; however, the precipitation totals following the mid-season samples exhibited a general decline, relative to the 30 year averages. In September, once physiological maturity (R6) had been reached, a fourth sample set was collected; at the final reproductive stage of crop development, the corn plant had ceased to sequester N from the soil solution and has begun to dry down. Similar to VT, the absence of a cover crop continued to limit the uptake potential of the corn crop. Relative to the control (285.10 kg ha^{-1}), cereal rye (373.26 kg ha^{-1}) and daikon radish (309.41 kg ha^{-1}) increased crop uptake at physiological maturity by 24 and 8%, respectively. While, at the end of growing season we observed that the addition of the cereal rye/daikon radish mixture (274.15 kg ha^{-1}) significantly reduced uptake potential relative to cereal rye (Fig. A-18).

Air temperatures following the 2015 spring soil samples (April-June) were again similar to the 30 year regional values, while total precipitation received was 71.6 mm greater. Despite rainfall totals much greater than regional averages, the early season (V6) crop uptake potential was not significantly limited in comparison to the previous growing season. In 2015, the crop accumulated a range of 10-16% of the total uptake by the sixth vegetative stage (Fig. A-19). At V6, both the daikon radish (43.30 kg ha^{-1}) and cereal rye (35.36 kg ha^{-1}) treatments increased uptake potential relative to the control (33.22 kg ha^{-1}). Though this difference was insignificant, this increase at V6 could potentially be attributed to the early season weather patterns, which created soil conditions that were conducive for soil nitrification, therefore any surplus precipitation could exponentially increase leaching potential. With apparent early season loss of the N source applied as inorganic fertilizer, inclusion of the daikon radish and cereal rye treatments increased crop uptake potential by 23 and 6% at V6, respectively. However, in contrast, the addition of the cereal rye/daikon radish mixture decreased uptake in comparison to the control treatment (21.92 kg ha^{-1}).

In the months of June and July (2015), heavily saturated soil conditions increased leaching potential, which potentially began to constrain crop growth. Similar to May, the months of June and July recorded precipitation totals that were greater than the regional averages. Frequent rainfall events created ponding within the field, thus sustaining soil moisture levels at or above field capacity. Receiving near record rainfall totals in those summer months (2015) created significant differences in crop uptake at V12 relative to the previous year (Table A-10). In conjunction with restrictive growing conditions, the absence of a cover crop treatment continued to reduce uptake potential in 2015. The daikon radish (130.12 kg ha^{-1}) demonstrated the ability to sequester on average the highest N concentration at V12 relative to the cereal rye/daikon radish mixture (119.12 kg ha^{-1}), control (109.37 kg ha^{-1}) and cereal rye (81.13 kg ha^{-1}) (Fig. A-19). In comparison to the control, the addition of daikon radish and the daikon radish mixture cover crop treatments increased corn uptake by 16 and 8%, respectively. Similar to V12, the VT data displayed significant annual differences (Table A-11); 2014 produced greater N concentrations relative to 2015. These annual differences can be attributed to the aforementioned weather patterns experienced in June and July. At tassel in 2015, continuous precipitation and warmer soil conditions aided in nitrification, thus leaving the remainder of inorganic fertilizer vulnerable to be leached below the rooting zone, effectively depleting soil N. This was evident in N uptake at VT for the control treatment as uptake did not increase from the recorded V12 values. The daikon radish (157.54 kg ha^{-1}) and cereal rye (127.41 kg ha^{-1}) treatments demonstrated the ability to sequester on average the highest N concentrations at VT relative to the control (113.95 kg ha^{-1}) and the cereal rye/daikon radish mixture (93.90 kg ha^{-1}) (Fig. A-19). The addition of the monoculture cover crop species, daikon radish and cereal rye increased N concentrations at tassel by 28 and 11%, respectively, however, this difference was found to be insignificant. Preceding the reproductive stage of the crop, the corn biomass within the control treatment had accumulated 50% of the total N. These values coincided with a study conducted at the University of Illinois, which determined up to 65% of the total crop N uptake is sequestered prior to R1 (Snyder, 2014). This is a substantial observation considering in 2015 under adverse growing conditions, the addition of daikon radish increased the N concentration prior to R1 to 58% of the total crop uptake.

Once physiological maturity (R6) had been reached in September of 2015, a fourth sample set was again collected. Environmental conditions experienced in June and July continued into the month of August, this significantly reduced N content in 2015 relative to the previous year (Table A-12). However, in 2015, despite adverse soil conditions, the control treatment was able to sequester 50% of the total N concentration subsequent to VT. Although there was no significant difference among treatments at R6 in 2015, the absence of a cover crop (contro1, 229.54 kg ha^{-1}) again reduced the total N concentration within the corn biomass relative to the monoculture (cereal rye, 343.67 kg ha^{-1}), (daikon radish, 271.28 kg ha^{-1}) cover crop species at the end of the growing season (Fig. A-19). Despite continuous large precipitation events, the trend for the monoculture cover crop species to increase the N content within the crop continued. In 2015, the addition of cereal rye and daikon radish treatments increased average R6 crop uptake by 25% or 77.94 kg ha^{-1}, relative to the control.

In order to quantify the general trends that occurred, we averaged the collective data for each treatment over the duration of two years (2014 and 2015). This allowed us to directly compare the total N concentration that was sequestered within each of the cover crop treatments relative to the control. According to cited literature, under a fall applied N system utilizing 170 kg ha^{-1}, V6 crop uptake (control treatment) in Iowa ranged from 11.9-20.9 kg ha^{-1} in 2001 and 3.7-14.3 kg ha^{-1} in 2002 (Licht and Al-Kaisi, 2005). In comparison, recorded 2014 and 2015 uptake values for the control treatment were 39.90 and 33.22 kg ha^{-1}, respectively. At V6 the addition of the daikon radish was the only treatment which increased crop uptake potential consistently both year relative to the control treatment (Fig. A-20). Both the cereal rye and cereal rye/daikon radish treatments demonstrated the capacity to maintain N uptake over the two year period in comparison to the control. Daikon radish, control, cereal rye and the cereal rye/daikon radish mixture accumulated 15, 14, 10 and 9% of the total N by V6, respectively. At V12, averaged data displayed the no cover crop control treatment reduced crop uptake relative to all cover crop species. The control values range from 109-134 kg ha^{-1}, these values coincide with multiple studies that reported approximate V12 uptake of a corn crop to be 131 kg ha^{-1} utilizing a 224 kg ha^{-1} N application rate (Girma et al., 2010). The no cover crop control treatment accumulated 47% of the total N by V12, in comparison to the addition of either daikon radish or the mixture, which increased V12 accumulation to a range of 49-56%. VT and R6 trends demonstrated the ability of the monoculture to extend and increase uptake potential late into the growing season. At R6 the cereal rye treatment sequestered a significantly higher N content than the no cover control, while the daikon radish treatment took up a greater concentration than the control, however, the difference was found to be insignificant (Fig. A-20).

Cover Cropping Effects on Corn Grain Yield

In 2014, yield was calculated using a weigh wagon and then corroborated with weights and percent moisture from the local grain cooperative. However, in 2015, data collection was near completion when an unforeseen accident caused the loss of all grain yield data. Therefore the 2015 yield data that will be presented will be calculated yield based upon R6 grain samples taken approximately one week prior to harvest; the two years will be presented and discussed separately.

Throughout the 2014 growing season the environmental conditions emulated the 30 year regional values; these conditions were conducive for soil mineralization and nitrification. However, occasionally saturated soil conditions could have possibly advanced leaching and denitrification processes. These weather patterns were potentially evident in the crop uptake data, displaying later season increases in total N content when a cover crop was present. Consequently, sampling at harvest also resulted in a yield difference between treatments, however no statistical differences were detected (Table A-13). In 2014, the control treatment yielded 12.8 Mg ha^{-1}. The absence of a cover crop reduced the crop yielding potential in the initial year for commercial grain by 6% relative to the monoculture cover crop species, thus resulting in a 0.8 Mg ha^{-1} decrease in yield (Fig. A-21). However, in comparison to other studies that documented cover crop impact on corn yield, we observed a yield increase, as the other studies documented either no effect or a decrease in yield. The documented decrease in yield was attributed to possible allelopathic effects of the rye, poor establishment and differences in soil properties (Pantoja et al., 2015; Olson et al., 2010; Moore et al., 2014; Reinbott et al., 2004). Due to timely establishment and proper management, we observed an increased yield for both the cereal rye and daikon radish treatments, which yielded 13.7 and 13.5 Mg ha^{-1}, respectively. On average the cereal rye/daikon radish mixture (12.7 Mg ha^{-1}) yielded the lowest, however the reduction in comparison to the control was minimal. The 2014 grain yields correlate with the R6 crop N uptake data; the addition of cover crops to a conventional system creates a biological impact on the crop and its ability to sequester nutrients and translate that into grain production. This coincides with survey data collected by CTIC and SARE; according to the survey the addition of a cover crop into a conventional cropping systems creates biological yield differences. Averaged survey data across the country (1,200 producers) displayed cover crop adoption increased corn yields by 2.1%; this is a consecutive trend observed over the past three years (Cover Crop Survey Report, 2015).

Annual difference between yields were not observed due to the loss of all 2015 yield data. However, calculated yields based upon collected R6 grain samples display similar trends as in 2014. In 2015, we observed ambient air temperatures that remained approximate with the regional averages, however, the precipitation totals received during May-August were substantially greater. The surplus 153 mm of rainfall that precipitated during that time frame created soil conditions that were consistently at or above field capacity, which increased the overall leaching and denitrification potential. This was evident within the R6 crop N uptake data, as previously mentioned, 2014 total N concentrations were significantly greater than those of 2015. Despite that, cereal rye (15.4 Mg ha^{-1}) again produced the highest yielding crop in 2015 (Fig. A-22). However, calculated yields estimated that the absence of a cereal cover crop only reduced yield by 0.1 Mg ha^{-1}. In contrast to cereal rye, the addition of either a daikon radish or a cereal rye/daikon radish mixture reduced yielding potential by 1.9 and 2.6 Mg ha^{-1}, respectively.

Conclusion

This study indicates that long-term cover crop integration positively impacted the distribution of spring inorganic N following fall application. The cereal rye treatment demonstrated the greatest capacity to influence N distribution over the four year period. At the agronomic depth, cereal rye on average reduced soil NO_3-N by 34% and increased the NH_4-N concentration by 46% in comparison to the control. Relative to the control, cereal rye reduced NO_3-N content by 35% at the environmental depths. The daikon radish/cereal rye mixture exhibited the ability to influence N in a similar manner as cereal rye; however, the percent reduction was not as noteworthy. Daikon radish created new trends at the agronomic depth, demonstrating the capacity to increase both NO_3-N by 17% and NH_4-N on average by 41%. In comparison to the control, fall applying N directly into daikon radish residue resulted in a 22% reduction of total soil NO_3-N within the 20-80cm portion of the soil profile.

Each year cold winter weather terminated the daikon radish three months prior chemical termination of the cereal rye and cereal rye within the mixture. As the result of mineralization and subsequent nitrification, daikon radish had equal or greater soil nitrate at the agronomic depth relative to the control, at the time of sampling 3-6 weeks before planting. However, the early season release of the inorganic N from the daikon radish residue increased the susceptibility to N loss in the spring. In contrast, both the cereal rye and cereal rye within the mixture had less time to decompose and nitrified N was less susceptible to loss due to spring precipitation.

This study has demonstrated that the addition of cover crops to a conventional cropping system impacted the concentration of total N at each of the sampled corn growth stages. According to cited literature (Snyder, 2014), uptake prior to R1 should be near or at 65% of the total; however, this study suggest that at VT the control averaged only 57% of the total N, while the addition of daikon radish increased that percentage of total N accumulated by VT to 63%. R6, total N content displayed the ability of the monoculture cover crop species to extend and increase uptake potential late into the growing season. On average the addition of cereal rye and daikon radish treatments increased average R6 crop uptake by 20% or 67.10 kg ha^{-1}. Consequently, sampling at harvest resulted in a yield difference between treatments. In 2014, the control treatment yielded 12.8 Mg ha^{-1}. The absence of a cover crop reduced the crop yielding potential in the initial year for commercial grain by 0.8 Mg ha^{-1} relative to the monoculture cover crop species, thus resulting in a 6% decrease in yield. 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 crop uptake efficiency resulted in equal or greater corn yield.

Multiple years of research have altered the way that producers perceive the use of cover crops. However, there is a need for long-term research to better understand the impact of cover crops and provide data to better educate producers on how to utilize various cover crop species within their current management strategies. As the primary focus has been placed on keeping reactive nitrogen from surface waters, little data has been compiled in order to see if the inclusion of cover crops is an economically feasible option for producers within the MRB. Previously conducted research has proven that cover crops have the potential to help meet long-term nitrogen management and reduction goals as set by the EPA. However, there is also a dearth of knowledge on the efficacy of large scale cover cropping and if the integration of cover crops will satisfy the reduction goals by the specific target date of 2025. Furthermore, if the reduction goals are not meet, how will government agencies respond and will impending regulations be placed on the timing, rate, placement and source of fertilizers used.

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CHAPTER IV

APPLIED EFFECTS OF COVER CROPS ON CORN UPTAKE AT CRITICAL GROWTH STAGES AND GRAIN YIELD WHEN EMPLOYING VARIABLE N APPLICATION RATES

Abstract

The inclusion of cover crops into a spring applied nitrogen (N) system has been shown to improve nitrogen efficiency, while maintaining crop yields. However, minimal research has been conducted on the influence cover crops have on fall applied N. Therefore, the objective of this research was to determine the applied effects of cover crops on grain yield and crop uptake at critical growth stages when employing alternate N application rates. The experimental site is located at the Illinois State University Research farm in Lexington, IL. The treatments consisted of a control, daikon radish, cereal rye and a cereal rye/daikon radish mixture. Each treatment was further divided into three nitrogen rate subplots: 200 kg N ha^{-1}, 145 kg N ha^{-1} and 90 kg N ha^{-1}applied in the form of anhydrous ammonia in the fall. Plant samples were collected at four specific corn growth stages (V6, V12, VT and R6). The early season crop within the daikon radish and cereal rye treatments absorbed a greater percentage of its total N for the season by V6 compared to the control. In comparison, the addition of cereal rye significantly ($P= 0.0021$) increased the total N content relative to all other treatments at physiological maturity. No obvious trend within the rate applied (90, 145 and 200 kg ha^{-1}) was observed. In 2014, despite application rate, the absence of a cover crop reduced the

yield potential by 3-6% relative to cereal rye (P= 0.0323) and the mixture. As a result of the increased yield despite rate, the cover crop treatments demonstrated the potential to reduce the necessary units of N to reach optimum yield and increase overall economic return. Therefore, the results of this study suggest that cover crop inclusion into a corn-corn rotation has the potential to advance nitrogen use efficiency, yield and profitability.

Introduction

Environmental concerns related to improper and excessive use of agricultural fertilizers are increasing as more research related to water quality becomes public knowledge. Due to this excessive use of industrially fixed nitrogen (Haber-Bosch), agriculture is considered one of the major sources of N loading to surface waters (Wortmann et al., 2004). The connection between N loading and agriculture has been strengthened by traditional cultural practices, which follow the general precedent of applying extra units of N based upon given field historical yield levels. While fertilizer use efficiency has greatly improved in U.S. agriculture the last 20 years, it is estimated that about 30% of N applied to crops is lost through leaching, volatilization, or denitrification (Waskom and Bauder, 2014). Due to rising input costs and impending government restrictions, the excess use of fertilizers will no longer be economically feasible, nor will it be acceptable to obtain new environmental objectives set by the EPA (Camberato, 2012). One of the most scrutinized best management practices is timing of N application. Studies have shown that timing of N application has a major influence on reactive N lost to surface waters. However, a 7 year study conducted by Randall and Vetsch directly compared fall versus spring N management strategies; the results demonstrated similar losses between the two systems. Conversely, in a year (1999) with abnormally high temperature and precipitation values, spring application increased corn yield by 25% and reduced NO_3-N loss compared with fall application (Vetsch and Randall, 2004). The results from that study determined that spring N application reduced NO_3-N leaching by 14% compared to fall (Randall and Vetsch 2005). Despite N loss potential and decreased corn yield, in some areas of the MRB approximately 50% of the nitrogen fertilizer is still applied in the fall (Smiciklas et al., 2008).

The inclusion of select species of winter annual cover crop into a conventional spring N management system has been shown to improve N use efficiency (Ditsch and Alley 1993). These annual cover crops have demonstrated the capacity to absorb residual, mineralized and recently applied inorganic fertilizer, inhibiting loss via the three primary loss pathways (Thorup-Kristensen et al., 2003). Due to the capacity of the cover crop to recycle nutrients, the concept of integrating reduced N rates with a cover crop to augment increased fertilizer prices and lower cash market grain prices has been gaining interest. Reeves et al (1993) reported based on multiple linear regression models, in the Coastal Plains region, the maximum economic return (grain yield) in a winter legume conservation tillage system were obtained with a decreasing rate of spring application throughout the duration of the study. However, this correlation between cover crop inclusion, application rate and corn grain yield within the MRB is not well documented under a fall applied N management system. Consequently, there is a dearth of knowledge in regard to the relationship between certain cover crop species, application rate and the efficacy of fall applied N in a commercial practice.

Therefore the objectives of this study are to (i) quantify the N uptake capacity of cereal rye, daikon radish and a cereal rye/daikon radish mixture to sequester residual and fall applied nitrogen (ii) determine how certain cover crops species influence cash crop uptake and yield when employing reduced N application rates. This study will allow for the assessment of the impact of different cover crop species on corn uptake efficacy and fall grain yields following fall N application into a living stand of cover crops.

Materials and Methods

The experimental site was located at the Illinois State University agriculture research farm in Lexington, Illinois. The predominant soil type that exists within the study site is Drummer El Paso silty clay loam. This soil type is poorly drained, and contains a slope of 0-2%. The cropping history of the field has been continuous corn (*Zea mays L.*) for the last 8 years to support silage production, and converted to a commercially harvested grain practice at the end of the 2013 growing season. The experimental location (54.88 m. in width east to west, 129.57 m. in length north to south), was divided into a total of 21 (.5 acre, .202 ha) plots. The research site was arranged in a split plot design with block replication; each plot (.5 acre, .202 ha) was further subdivided into three subplots, which contained alternate N application rates. The N rates chosen for this study were based upon the suggested MRTN (Maximum return to Nitrogen) of 200 kg N ha^{-1} for central Illinois developed by the N rate calculator (Iowa State University). Subsequent rates decreased by increments of 55 kg N ha^{-1}, to determine the effects of reduced rates and cover crop inclusion.

Research variables:

- Nitrogen application rates (200 kg ha^{-1}, 145 kg ha^{-1}, 90 kg ha^{-1}).
- Cover crop treatments (control (no cover crops), daikon radish (*Raphanus sativus L.*), cereal rye (*Secale cereal L.*), and daikon radish/ cereal rye blend).

These independent variables were designated to establish the capacity of the cover crop and alternate nitrogen application rates to impact the total N uptake at critical growth stages and overall grain yield (dependent variables).

Cultural Practices

For application purposes, the study followed major agricultural practices within the MRB. Application dates were based on an annual basis due to in-season weather variability. An early maturity corn hybrid (2,620 Growing Degree Days, GDD) was planted in the month of May (2014 and 2015) with a 12 row John Deere planter at 85,250 seeds per hectare. The row spacing used was 76.2 cm, which is the predominant spacing used within the region. In-season weed control was achieved with a Glyphosate herbicide application before the corn reached the eighth vegetative stage (V8). In September (2014-2015) the crop was commercially harvested once it reached maturity; moisture at harvest was 20%. After harvest was completed, the cover crop treatments were drilled into existing crop residue from conventional harvesting practices. The cover crop seeding rates used were developed by the sustainable agriculture research and education program.

Table 1

Cover Crop Seeding Rates

Cover Crop Species	Land Area (Hectare)	Seeding Rate (kg/ha^{-1})	Kg. Seed needed
Cereal Rye	0.61	67.2	41.0
Daikon Radish	0.61	6.70	4.10
Cereal Rye (85%)/Daikon Radish (15%)	0.61	56.1	84.1

Note. Data gathered from the Sustainable Agriculture Research and Education Program (2015)

The application of nitrogen occurred once the average daily soil temperature fell below 10°C. The N source was applied directly into a living stand of cover crops in the form of anhydrous ammonia prior to the primary crop growing seasons (Figure 1).

Figure 1. Fall application of anhydrous ammonia into a living cover crop stand

Throughout the duration of the study, daikon radish plants winter terminated in December from subfreezing temperatures and vegetative desiccation. In the spring, chemical termination of the cereal rye was accomplished using a non-selective herbicide (Glyphosate and 2, 4-Dichlorophenoxyacetic acid) to eradicate the cover crop stand approximately two weeks before the anticipated planting of the cash crop. Seedbed preparation prior to corn planting was achieved with a soil finisher upon the complete necrosis of the cover crop.

Plant Sampling

Representative cover crop samples were obtained using a random selection process. Within each treatment, four 0.6858 m^2 quadrants were collected to create a composite cover crop sample. This sampling technique was modified from a method developed by Dean and Weil in 2009. Cover crop growth was documented and sampled in both the fall and spring seasons. The above ground biomass was sampled within each of the cover crop treatments; no samples were collected from the control treatment. All of the samples were oven dried at 60ºC, weighed and ground to pass through a 1-mm. sieve. Total percent nitrogen determination is achieved using a dry combustion method; a 0.1000 g. sample was analyzed via LECO FP-528 N Analyzer. Dry weight of each sampling quadrant was quantified and used to determine overall biomass and total nitrogen uptake. Nitrogen uptake was calculated by multiplying %N by total biomass (kg ha^{-1}). Growing degree days (GDD) were calculated for each growing season, to correlate cover crop biomass and N uptake with trends observed in soil distribution and subsequent crop uptake and yield. To calculate GDD, a base of 0°C was used; the calculation for winter annual crops was derived from Montana State University (Miller et al., 2001).

Cash crop samples were taken at critical development stages throughout the growing season. The growth stages and sampling points that were considered critical are based upon previously conducted research involving nutrient uptake and total N (V6, V12, VT and R6). Population density was conducted twice within each treatment in a random fashion during each critical growth stage sampling. One one-thousandth of an acre was represented using a 5.334 m constant, from this measurement two whole plant samples from each treatment were procured and analyzed collectively. Reproductive growth stage samples were further divided into sample subsets (grain, cob, lower stalk, and the remainder of the plant). Corn grain yield and moisture content data were analyzed after the completion of each harvest season. Yield was calculated using weights collected from a verified weigh wagon, those weights were then corroborated by the local grain cooperative. The samples were oven dried at 60°C, weighed and ground to pass through a 1-mm sieve. Total percent nitrogen determination is achieved using a dry combustion method; a 0.1000 g sample was analyzed via LECO FP-528 N Analyzer. Total N data was used to establish nitrogen uptake for each treatment. Nitrogen uptake was calculated by multiplying %N by total biomass (kg ha^{-1}).

Statistical Analysis

The research formatting used for the duration of this study was a split-plot design with three replications. Cover crop N uptake and biomass and crop N uptake and yield analysis was conducted using split-plot modeled ANOVA as calculated by PROC GLM. Cover crop treatments, rate and year were considered fixed effects, while block was treated as a random variable. LS-Means and REGWQ (Ryan-Einot-Gabriel-Welsch Q test) comparisons tests were used to compare treatments to each other and to the control. Orthogonal contrast was used to determine yield significance between treatments and application rates. A P level of <0.05 was used to determine significant differences between treatments.

Results and Discussion

Environmental Conditions

Documented weather patterns during the 2013-2015 growing seasons allowed for the assessment of cover crop impact on corn N uptake and yield under dynamic weather conditions. The average annual ambient air temperatures for 2013-2014 and 2014-2015 were 8.7 and 10.6°C, respectively (Fig. B-1). The mean temperature for 2014 was well below 30 year average of 10.8°C; however, 2015 was comparable with an annual average air temperature of 10.6°C.

In 2014, the average ambient air temperatures were considerably below the aforementioned 30 year average temperature. Annually, 2014 was 2.1°C cooler than the 30 year average. The lowest recorded temperatures observed throughout the duration of the study were in the months of January and February 2014, -8.9 and -9.0°C; 5.1 and 6.9°C lower than the regional average, respectively. However, the months to follow were consistently similar to the 30 year values. April-October recorded average temperatures within 1°C of the average regional temperature.

The average temperature in 2015 was 10.6°C, which was only 0.2°C lower than the 30 year average temperature. However, during the late winter and early spring months in 2015, the ambient air temperatures were significantly cooler than the 30 year average with January, February and March -0.8, -6.1 and -1.9°C cooler relative to the 30 year average, respectively.

Annual precipitation in 2014 was 166.9 mm below the 30 year average of 972.8 mm (Fig. B-2). The first 5 months of the year created the majority of that deficit with January, February, March, April and May receiving 35.2, 32.3, 21.2, 31.2 and 43.3 mm less than the regional averages. However, during the cash crop growing season the average rainfall total was similar to the 30 year average. During the months of May-September, the 2014 total precipitation received was only 3.6 mm less than the regional average.

In 2015, annual precipitation totals were approximately 1,057 mm, thus receiving 84 mm more than the 30 year regional average. The largest concentration of total precipitation came in the form of rainfall during the summer months, May, June, July and August receiving 23.5, 78.5, 40.9 and 9.9 mm more than the regional 30 year averages, respectively. Ensuing average rainfall values in the fall, the winter months of November and December recorded uncharacteristically warm temperatures. This temperature flux supplemented large amounts of rainfall that are atypical for the region; in the months of November and December 251.7 mm of total precipitation was recorded, this being 112.9 mm greater than the regional average.

Cover Crop Shoot Dry Matter and Nitrogen Uptake

The various weather patterns experienced throughout the 2013-2015 cover crop seasons allowed for data collection to occur under two diverse growing seasons. Under these conditions, cover crop performance was evaluated for biomass production and N sequestration potential. For the intended purposes of this study, the N scavenging ability of the aforementioned cover crop treatments were documented to determine the capacity to improve the efficacy of fall applied N at multiple rates of application (90, 145 and 200 kg ha^{-1}). No significant three-way interactions were observed between treatment, year, and application rate within this study. Hence discussion of the results will focus on two-way interactions and main effects as appropriate. Sampling the cover crop in both the fall and spring (2013-2015), resulted in a significant interaction between year sampled and cover crop species for both biomass and total N uptake (Table B-9) (Table B-10). However, the rate subsample data for the 2013-2015 seasons were only collected within the cereal rye and cereal rye/daikon radish treatments. This is due to the later application of anhydrous ammonium to satisfy the recommended soil temperature minimum and the early winter senescence of the daikon radish treatment that occurred in 2013. This effectively kept us from establishing the multiple N rates prior to senescence of the daikon radish.

The 2013-2014 cover crop growing season displayed cooler ambient air temperatures, with January (-8.9°C) and February (-9.0°C) being the coldest months on record throughout the duration of the study. Annual anhydrous ammonia application occurred mid-December; however, the below average regional temperatures limited cover crop growth potential throughout the season, with a total of 1679 GDD accumulated during the months of September-April (Table B-2). Early senescence of the daikon radish led to limited biomass production (1450.3 kg ha^{-1}) and N uptake (38.1 kg ha^{-1}) at 200 kg N ha^{-1} (Table B-5) (Table B-6). Subsequent spring weather patterns continued to diminish growing degree day accumulation. Despite an additional 443 spring GDD, cereal rye (200 kg N ha^{-1}) dry matter accumulation (706.8 kg ha^{-1}) and total N uptake (35.1 kg N ha^{-1}) were limited relative to daikon radish. In 2013-2014 the mixture recorded the lowest biomass (670.2 kg ha^{-1}) and total N (32.5 kg N ha^{-1}).

Biomass production for cereal rye at 145 kg N ha^{-1} (809.3 kg ha^{-1}) and 90 kg N ha^{-1} (798.9 kg ha^{-1}) were greater relative to 200 kg N ha^{-1} (706.8 kg ha^{-1}), respectively (Table B-7) (Table B-8). Similar to biomass, total N content for cereal rye at 145 kg N ha^{-1} (36.2 kg ha^{-1}) and 90 kg N ha^{-1} (36.1 kg ha^{-1}) were greater relative to 200 kg N ha^{-1} (35.1 kg ha^{-1}), respectively. Consequently, there were no correlations observed for rate of application with an increase in either biomass or total N content. This could potentially be attributed to the restrictive weather patterns that inhibited the cover crop from interacting with the N available within the soil solution. By increasing the rate of application 38%, from 90 kg N ha^{-1} to 145 kg N ha^{-1}, the relative biomass production and total N for cereal rye increased by a minimal percentage (<1%). This trend was not observed within the cereal rye/daikon radish treatments, both biomass and total N content increased linearly with application rate. In 2013-2014, the mixture recorded biomass totals at 200 kg N ha^{-1} (670.2 kg ha^{-1}), 145 kg N ha^{-1} (657.8 kg ha^{-1}) and 90 kg N ha^{-1} (586.1 kg ha^{-1}), respectively and total N values at 200 kg N ha^{-1} (32.5 kg ha^{-1}), 145 kg N ha^{-1} (32.1 kg ha^{-1}) and 90 kg N ha^{-1} (28.4 kg ha^{-1}), respectively. Increasing the rate by 38% for the mixture increased biomass production by 11% and total N content by 12%. Therefore, rate of application had a greater influence on the cereal rye/daikon radish mixture. However, despite application rate, the cereal rye monoculture demonstrated the capacity to greater influence average biomass (771.7 kg ha^{-1}) and total N content (35.8 kg ha^{-1}) relative to the mixture (638.1 kg ha^{-1}) (31.0 kg ha^{-1}). A trend, which was also observed in a study conducted in the Northeastern United States, where they found that cereal rye mixtures displayed an intermediate N content relative to pure stands or monocultures of cereal rye (Ketterings et al., 2015). This also agrees with Poffenbarger and Weil 2014, who found that cereal rye N content decreases linearly with increasing biomass of the additional cover crop species within the mixture.

Due to a productive corn crop in 2014, little residual N remained after harvest. Rather than succeeding silage, the cover crop was sewn directly into a dense corn residue. Monthly ambient temperatures (September-April) were again well below 30 year regional averages; which, limited the quantity of GDD accumulated in the fall (Table B-2). With the fewest fall GDD accumulated, minimal N available for uptake, and dense residual ground cover, the daikon radish biomass production (638.4 kg ha^{-1}) totaled a 66% reduction relative to 2013-2014 at the 200 kg N ha^{-1} rate of application, while the N uptake value (31.9 kg ha^{-1}) was maintained (Table B-5) (Table B-6). In contrast to the previous cover crop season, an extended spring growth period (649 total GDD) allowed for exponential cereal rye development; which, significantly increased both biomass production (2159.9 kg ha^{-1}) and N uptake (107.2 kg N ha^{-1}) (Table B-3) (Table B-4). Though insignificant, the mixture emulated the cereal rye and demonstrated an increase in both biomass (978.3 kg ha^{-1}) and total N uptake (52.3 kg N ha^{-1}) relative to the previous season.

The increase in spring GDD in 2014-2015, improved the ability of the cover crop species to interact with available soil N (Table B-2). However, similar to 2013-2014, there were again no correlations observed for rate of application with an increase in either biomass or total N. In 2014-2015, we observed that the cereal rye at 145 kg N ha^{-1} again demonstrated the capacity to produce a greater biomass (2446.9 kg ha^{-1}) and increased the total N (112.6 kg ha^{-1}) content relative to 200 kg N ha^{-1} (2159.9 kg ha^{-1}) (107.3 kg ha^{-1}) and 90 kg N ha^{-1} (2089.8 kg ha^{-1}) (104.4 kg ha^{-1}), respectively (Table B-7) (Table B-8).

Conversely, in 2014-2015, the mixture at the lowest rate (90 kg N ha^{-1}) recorded a higher biomass (1312.0 kg ha^{-1}) and total N content (67.5 kg ha^{-1}) relative to the 145 kg N ha^{-1} (1258.9 kg ha^{-1}) (65.5 kg ha^{-1}) and 200 kg ha^{-1} (978.3 kg ha^{-1}) (52.3 kg ha^{-1}). In a year with warmer spring ambient air temperatures, the relative biomass production and total N for cereal rye increased by 15 and 7%, respectively when the application rate was altered from 90 to 145 kg N ha^{-1}. However, in 2014-2015, with the increase in rate applied, we observed a 4 and 3% decrease in biomass production and total N for the mixture, respectively. According to University of Nebraska extension soil specialist, Richard Ferguson, 2009; applying an excess of fertilizer to a living crop (corn) may result in injuries from an excess of salts or ammonia. Therefore stunting growth both above (leaf burn) and below ground (primary roots). Applying this principal to our study could potentially explain the decrease in biomass and uptake as N rate increase.

In order to recognize the trends that occurred, we averaged the collective biomass and N uptake data for each treatment over the duration of the two year study. This allowed us to directly compare the average biomass production and total N for each treatment. Sampling the cover crop in the fall and again in the spring two weeks before termination, resulted in a significant difference in both total uptake and biomass production between cereal rye and the cereal rye/daikon radish mixture despite the application rate (Table B-9) (Table B-10). However, when considering rate (200, 145 and 90 kg ha^{-1}) as a main effect, we observed no differences in biomass or total N content for cereal rye or the mixture. Average above ground biomass production (2013-2015) for the monoculture cover crop species (cereal rye), despite rate applied was 1501.9 kg ha^{-1}. In comparison to studies conducted by Kasper and Bakker, 2015, cereal rye biomass production over a four year period (2006-2009) averaged 1894 kg ha^{-1}. Due to weather conditions experienced over the two year period, N uptake ranged from 32-38 kg ha^{-1}, 35-108 kg ha^{-1} and 31-62 kg ha^{-1}for daikon radish (200 kg ha^{-1} only), cereal rye and the mixture (despite rate), respectively. Within our study, cereal rye demonstrated the ability to sequester the highest N concentration in comparison to daikon radish and the mixture. Under adverse growing conditions, the data suggests that on an annual basis, these cover crop species have to ability to absorb 15-54% of the fall N within central Illinois, assuming a standard range of N rates applied (200-224 kg ha^{-1}).

Influence of Alternative N Rates and Cover Crop Inclusion on Corn Nitrogen Uptake

In order to quantify the long term effects of cover cropping on a conventional crop production system, corn N uptake (Total N) was measured throughout the 2014 and 2015 corn growing seasons at critical growth stages. The corn biomass and uptake data, in conjunction with yield data aided in determining how the corn crop responds when introduced into a long-term cover crop management system with multiple application rates of fall N (90, 145 and 200 kg ha^{-1}). No significant three-way or two-way interactions were observed between treatment, year, and application rate, so the discussion of crop uptake by growth stage results will focus on main effects as appropriate (Table B11-14) (Table B15-18). Due to the later application of anhydrous ammonium to satisfy the recommended soil temperature minimum and the early winter senescence of the daikon radish treatment that occurred in 2013 kept us from establishing the daikon radish within the subplot rates. Therefore, similar to the cover crop data, rate subsample data (all rates) for crop uptake were only collected within the cereal rye, cereal rye/daikon radish and control treatments.

On average (2014-2015), at V6, the addition of cereal rye despite year and rate applied increased crop uptake comparative to both the control and mixture; however, this difference was only significant in comparison to the mixture (Fig. B-14). In 2014, the environmental conditions were conducive for soil mineralization and nitrification, with a sufficient nutrient supply available in the soil solution, the early season crop was able to sequester a range of 8-14% of the total uptake by the sixth vegetative stage. However, there were no correlations observed for rate of application with an increase in total N. In 2014, cereal rye demonstrated the capacity to increase crop uptake at V6 in comparison to the control at 145 and 90 kg N ha^{-1}, while the mixture only increased total N relative to the control at 145 kg N ha^{-1} (Fig. B-6). At the 200 kg N ha^{-1} rate, the daikon radish treatment demonstrated the ability to sequester on average the highest N content (43.56 kg ha^{-1}) at V6 relative to the control (39.90 kg ha^{-1}), cereal rye (31.64 kg ha^{-1}) and the cereal rye/daikon radish mixture (29.15 kg ha^{-1}), respectively (Fig. B-3). Though this difference at 200 kg N ha^{-1} was insignificant, this slight increase at V6 for daikon radish, could potentially be attributed early season mineralization and increased N retention within the upper depth of the soil profile. Conversely, according to a summary of other studies conducted by USDA-ARS, the reduction observed for cereal rye at the highest rate could potentially be due to residual and fertilizer N immobilization (Dabney et al., 2001). Although we observed a contribution from the cereal rye at the subsequent rates, the lack of significance could mean that the available source of N applied as an inorganic fertilizer in the fall was sufficient for the corn crop to have reached its early season N uptake capacity.

Following the V6 samples in 2014, the weather conditions in the months of June and early July were similar to the 30 year regional averages; growing conditions continued to be ideal for soil mineralization and subsequent nitrification. Both V12 and VT samples were collected in the second-third week in July. On average at V12, despite year and rate, the addition of a cover crop increased the total N content by a range of 3-15% relative to the control (Fig. B-14). However, this was not the trend for 2014; as the inclusion of the mixture decreased N content in comparison to the control. Contradictory to V6, V12 N content increased with application rate in 2014 (Fig. B-8). Although this difference was found to be insignificant, this demonstrates a greater response to additional units of N at points of rapid growth and uptake within the growing season. These findings are in agreement with those by Dharmakeerthi et al., (2006), where plants growing in treatments with higher N application took up significantly more N at critical growth stages. At 200 kg N ha^{-1}, the cereal rye (187.12 kg ha^{-1}) demonstrated the ability to sequester on average the highest N content at V12 relative to the cereal rye/daikon radish mixture (159.47 kg ha^{-1}), daikon radish (156.70 kg ha^{-1}) and control (134.78 kg ha^{-1}) (Fig. B-3). At the suggested MRTN application rate of 200 kg N ha^{-1}, the corn crop was able to sequester a range of 50-58% of the total uptake by the twelfth vegetative stage as a result of cover crop inclusion, in comparison to the control which accumulated only 47% of the total uptake.

The following weather conditions experienced through VT were conducive for crop growth, but continually saturated soil conditions potentially could have advanced leaching and denitrification processes. In 2014, the corn crop within the control treatment continued to display reduced N uptake values; despite year, both the cereal rye and the mixture sequester a high N concentration comparative to the control at both 145 and 90 kg N ha^{-1} (Fig. B-10). At 200 kg N ha^{-1}, the control (178.09 kg ha^{-1}) treatment displayed a 16% reduction in total N uptake values in comparison to the cereal rye (213.28 kg ha^{-1}) and daikon radish (209.90 kg ha^{-1}) treatments at tassel (Fig. B-3). However, the continued absence of significance between the treatments demonstrated the capacity of the inorganic fertilizer applied in the fall to sustain crop development through the final vegetative growth stage.

The ambient air temperature throughout the remainder of the 2014 growing season remained consistent with the regional average values; however, the precipitation totals following the mid-season samples exhibited a general decline, relative to the 30 year averages. Once physiological maturity (R6) was reached in September, a fourth sample set was collected. At this final reproductive stage of corn development, the corn plant has ceased nutrient uptake from the soil solution and has begun to dry down. Similar to VT, the absence of a cover crop limited the uptake potential of the corn crop. At R6, the addition of cereal rye, despite year and rate applied, significantly increased crop uptake comparative to both the control and the mixture (Fig. B-14). On average (2014-2015), the addition of cereal rye and daikon radish (200 kg N ha^{-1}) increased the total N content by 19 and 28%, respectively, relative to the control (Fig B-5). This was also the trend for 2014; however the differences were found to be insignificant. Optimal growing conditions allowed natural soil mineralization to continue well into the reproductive stages of the crop, therefore reducing the dependency upon the applied fertilizers. As a result, we observed comparable N concentrations between treatments at subsequent rates of N application.

In 2015, the average air temperature following the spring cover crop samples (April-June) was similar to the 30 year regional value; however, the total precipitation received was 71.6 mm greater. Despite rainfall totals much greater than regional averages, the early season (V6) crop uptake potential was not significantly limited in comparison to the previous growing season. The cereal rye treatment increased total N content within the crop at V6, relative to the mixture and control despite the rate of application. Despite year, the daikon radish treatment at 200 kg N ha^{-1} demonstrated the capacity to increase N content relative to all treatments, this difference was only significant relative to the mixture (21.92 kg ha^{-1}) (Fig. B-14). In 2015, at 200 kg N ha^{-1}, both the daikon radish (43.30 kg ha^{-1}) and cereal rye (35.36 kg ha^{-1}) treatments increased uptake potential at V6 relative to the control (33.22 kg ha^{-1}) by 23 and 6%, respectively (Fig. B-4). At 145 kg N ha^{-1}, cereal rye was the only treatment that demonstrated the capacity to increase total N relative to the control (Fig. B-7). However, at 90 kg N ha^{-1}, both cereal rye and the mixture increased crop uptake at V6 in comparison to the control. With more rainfall, the greater the opportunity for leaching and denitrification. The presence of a cover crop protects a large portion of the N within the organic form, which increases organic material and supports in-season mineralization. This is reaffirmed by an Oregon State University Extension study, which established that cover crop N uptake is a good indicator of the PAN to be released to the subsequent cash crop following incorporation. However, their cover crop incubation study also found that usually less than 50% of the total cover crop N uptake is released as PAN during the first year of integration (Sullivan and Andrews, 2012).

June and July recoded precipitation values that were greater than the regional averages with near record rainfall totals. Frequent rainfall events created ponding within the field, thus sustaining soil moisture levels at or above field capacity, which increased the potential for leaching and denitrification. Thus, creating significant differences in crop uptake at V12 relative to the previous year (Table B-16). In conjunction with restrictive growing conditions, the absence of a cover crop treatment continued to reduce uptake potential in 2015. At 145 and 90 kg N ha^{-1}, both the cereal rye and the mixture demonstrated the capacity to increase total N relative to the control (Fig. B-9). At 200 kg N ha^{-1}, the daikon radish (130.12 kg ha^{-1}) treatment demonstrated the ability to sequester the highest N content at V12 relative to the cereal rye/daikon radish mixture (119.12 kg ha^{-1}), control (109.37 kg ha^{-1}) and cereal rye (81.13 kg ha^{-1}) (Fig. B-4). In comparison to the control, the addition of daikon radish and the mixture cover crop treatments increased corn uptake by 16 and 8%, respectively at V12. Though this difference was insignificant, the trend for cover crop inclusion to increase N content was observed for all three rates within a single growth stage. The weather patterns could have resulted in net mineralization and a faster N release rate, therefore increasing N availability to soil microorganisms (Paul and Clark, 1996; Grant et al., 2002).

Similar to V12, the VT data displayed significant annual differences; 2014 produced greater N concentrations relative to 2015 (Table B-17). These annual differences can be attributed to the aforementioned weather patterns experienced in June and July. At tassel in 2015, continuous precipitation and warmer soil conditions aided in nitrification, thus leaving the remainder of inorganic fertilizer vulnerable to be leached below the rooting zone, effectively depleting soil N. This was evident in N uptake at VT for the control treatment at 200 kg N ha^{-1}, as uptake did not increase from the recorded V12 values (Fig. B-4). The daikon radish (157.54 kg ha^{-1}) and cereal rye (127.41 kg ha^{-1}) treatments demonstrated the ability to sequester on average the highest N content at V12 relative to the control (113.95 kg ha^{-1}) and the cereal rye/daikon radish mixture (93.90 kg ha^{-1}). At 200 kg N ha^{-1}, the addition of daikon radish and cereal rye increased N uptake at tassel by 28 and 11%, respectively. However, this was not the trend for the lower rates. At 145 and 90 kg N ha^{-1}, we observed a comparable N uptake for all treatments (Fig. B-11). Preceding the reproductive stage of the crop, the corn biomass within the control treatment had accumulated 61% of the total N despite the rate applied. These values coincided with a study conducted at the University of Illinois, which determined up to 65% of the total crop N uptake is sequestered prior to R1 (Snyder, 2014). This is a substantial observation considering in 2015 under adverse growing conditions, the addition of daikon radish increased the N content prior to R1 to 74% of the total crop uptake.

Once physiological maturity (R6) had been reached in September of 2015, a fourth sample set was again collected. Environmental conditions experienced during the months of June and July continued into August. The R6 crop uptake data displayed significant differences in N uptake with the 2014 R6 samples recording significantly greater N content relative to the 2015 samples (Table B-18). This annual reduction is attribute to the effectively depleted soil solution, which limited uptake as the crop transitioned into the reproductive stage. At R6, the addition of cereal rye, despite year and rate applied, significantly increased crop uptake comparative to both the control and mixture (Fig. B-14). Although there was no significant difference among treatments at 200 kg N ha^{-1}, the absence of a cover crop (control, 229.54 kg ha^{-1}) again reduced the total N content within the corn biomass relative to the monoculture cover crop species (cereal rye, 343.67 kg ha^{-1}) (daikon radish, 271.28 kg ha^{-1}) at the end of the growing season (Fig. B-4). In 2015, the addition of cereal rye and daikon at 200 kg N ha^{-1} increased R6 crop uptake by an average of 25% relative to the control. This study has demonstrated that the addition of cover crops into a conventional cropping system impacted total N uptake at each of the sampled corn growth stages. Total N content at physiological maturity demonstrated the capacity of the monoculture cover crop species to extend and increase uptake potential late into the growing season.

Influence of Alternative N Rates and Cover Crop Inclusion on Corn Grain Yield

In 2014, yield was calculated using a weigh wagon and then corroborated with weights and percent moisture from the local grain cooperative. However, in 2015, data collection was near completion when an unforeseen accident caused the loss of all grain yield data. Therefore the 2015 yield data that is presented was calculated yield based upon R6 grain samples taken approximately one week prior to harvest; the two years are presented and discussed separately.

Throughout the 2014 growing season the environmental conditions emulated the 30 year regional values; these conditions were conducive for soil mineralization and nitrification. However, occasionally saturated soil conditions could have prompted leaching and denitrification. These weather patterns were evident in the crop uptake data, displaying later season increases in total N concentration when a cover crop was present.

The 2014 grain yield were highly correlated with the R6 N uptake data. The addition of cover crops created a significant and biological impact on the crop and its ability to sequester nutrients, which translated into grain production. However, other studies documenting the impact of cover crops on corn yield, observed either no effect or a decrease in yield. The documented explanations for the decrease in yield were either allelopathic effects of the rye, poor establishment or differences in soil properties (Pantoja et al., 2015; Olson et al., 2010; Moore et al., 2014; Reinbott et al., 2004). In 2014, the control treatment yielded 12.8 Mg ha^{-1} at 200 kg N ha^{-1}. The absence of a cover crop reduced the crop yielding potential in the initial year for commercial grain by 6% relative to the monoculture cover crop species, thus resulting in a 0.8 Mg ha^{-1} decrease in grain yield (Fig. B-15). Due to timely establishment and proper management of the cover crop in 2014, we observed an increase in N efficacy.

Although the ANOVA (Table B-20) displayed no statistical differences between the treatments at the subsequent rates, we did observe statistical differences between treatments, despite rate using an orthogonal contrast. Despite application rate, the addition of a cereal rye cover crop significantly increased yield (Table B-21). In 2014, the average yield for the control treatment was 12.7 Mg ha^{-1}. Despite optimal growing conditions, there was no response of the corn crop to the additional N within a cover crop treatment; the average yield for both cereal rye and the mixture at all three rates was 13.2 Mg ha^{-1}. The absence of a cover crop reduced the crop yielding potential in the initial year for commercial grain by a range of 3-6% (Fig. B-17). As a result of the increased yield despite rate, the cover crop treatments demonstrated the potential to reduce the necessary units of N to reach optimum yield and increase overall economic return. This coincides with survey data collected by the CTIC and SARE, which validates the addition of a cover crop into a conventional cropping systems. Surveyed producers from across the country (1,200 producers) reported cover crop adoption increasing corn yields by 2.1%. This increase was a consecutive trend, which has been observed over the past three years (Cover Crop Survey Report, 2015).

Annual difference between years were not assessed due to the loss of all 2015 yield data. However, no significant two-way interaction was observed between treatment and application rate. In 2015, calculated yields based upon R6 grain samples displayed significant differences for both main effect sources (treatment and rate) (Table B-23). We observed a surplus of 153 mm of rainfall during May-August (2015). Thus, creating soil conditions that were consistently at or above field capacity throughout the latter part of the growing season. Due to these conditions, corn yield was increased with increasing rates of applied N; the application rates of 200 (REGWQ, df= 22, P <0.0001) and 145 kg N ha^{-1} (REGWQ, df= 22, P= 0.0003) significantly increased yield relative to lowest rate of 90 kg N ha^{-1}. In 2015, corn yield responded inversely relative to the previous season, the addition of cover crops negatively impacted yield. Despite the potential of increased rates of leaching and denitrification, the control treatment despite rate demonstrated the capacity to increase yield relative to all cover crop treatments (Fig. B-20); however, this difference was only significant in comparison to the mixture (Table B-24).

Conclusion

This study indicates that long-term cover crop integration positively impacted the corn uptake at critical growth stages, while demonstrating the capacity to either increase or maintain corn yields. Sampling the cover crop in the fall and again in the spring two weeks before termination, resulted in a significant difference in both total uptake and biomass production between cereal rye and the cereal rye/daikon radish mixture despite the application rate. We observed no differences in biomass or total N content between the application rates (200, 145 and 90 kg ha^{-1}) for cereal rye or the mixture. Due to the variable weather conditions experienced over the two year period, N uptake ranged from 32-38 kg ha^{-1}, 35-108 kg ha^{-1} and 31-62 kg ha^{-1}for daikon radish (200 kg ha^{-1} only), cereal rye and the mixture (despite rate), respectively. Cereal rye demonstrated the ability to sequester the highest N concentration in comparison to daikon radish and the mixture. Under adverse growing conditions, the data suggests these cover crop species have to ability to absorb 15-54% of the fall N in the Upper Mississippi River Basin, assuming a standard range of N rates applied (200-224 kg ha^{-1}).

This study has proven that corn N uptake and yield can be influenced by the inclusion of select cover crop species. Annual trends demonstrate that in years with large amounts of N being lost (2015), that cover crop inclusion has a greater influence on corn N uptake. However, despite year, the addition of the monoculture cover crop species effectively extended uptake potential late into the growing season, increasing the total N content at physiological maturity. On average, at 200 kg N ha^{-1} the addition of cereal rye and daikon radish treatments increased R6 crop uptake by 20%. At R6, we observed significant differences between application rates, 200 kg N ha^{-1}, demonstrated the capacity to increase corn N uptake relative to 145 and 90 kg N ha^{-1}. However, despite rate applied, cereal rye significantly increased total N content at R6, relative to both the control and the cereal rye/daikon radish mixture. In 2014, the absence of a cover crop reduced the crop yielding potential in the initial year for commercial grain by a range of 3-6% relative to cereal rye and the mixture. As a result of the increased yield despite rate, the cover crop treatments demonstrated the potential to reduce the necessary units of N to reach optimum yield and increase overall economic return. Despite weather extremes, the data demonstrated that fall applying N into a living stand of cover crops improved the crop uptake efficiency resulted in equal or greater corn yield.

Multiple years of research have altered the way that producers perceive the use of cover crops. However, there is a need for long-term research to better understand the impact of cover crops and provide data to better educate producers on how to utilize various cover crop species within their current management strategies. As the primary focus has been placed on keeping reactive nitrogen from surface waters, little data has been compiled in order to see if the inclusion of cover crops is an economically feasible option for producers within the MRB. Previously conducted research has proven that cover crops have the potential to help meet long-term nitrogen management and reduction goals as set by the EPA. However, there is also a dearth of knowledge on the efficacy of large scale cover cropping and if the integration of cover crops will satisfy the reduction goals by the specific target date of 2025. Furthermore, if the reduction goals are not meet, how will government agencies respond and will impending regulations be placed on the timing, placement and source of fertilizers used.

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CHAPTER V

CONCLUSION

This study indicates that long-term cover crop integration positively impacted the distribution of spring inorganic N following fall application. The cereal rye treatment demonstrated the greatest capacity to influence N distribution over the four year period. At the agronomic depth, cereal rye on average reduced soil NO_3-N by 34% and increased the NH_4-N concentration by 46% in comparison to the control. Relative to the control, cereal rye reduced NO_3-N content by 35% at the environmental depths. The daikon radish/cereal rye mixture exhibited the ability to influence N in a similar manner as cereal rye; however, the percent reduction was not as noteworthy. Daikon radish created new trends at the agronomic depth, demonstrating the capacity to increase both NO_3-N by 17% and NH_4-N on average by 41%. In comparison to the control, fall applying N directly into daikon radish residue resulted in a 22% reduction of total soil NO_3-N within the 20-80cm portion of the soil profile.

Each year cold winter weather terminated the daikon radish three months prior chemical termination of the cereal rye and cereal rye within the mixture. As the result of mineralization and subsequent nitrification, daikon radish had equal or greater soil nitrate at the agronomic depth relative to the control, at the time of sampling 3-6 weeks before planting. However, the early season release of the inorganic N from the daikon radish residue increased the susceptibility to N loss in the spring.

In contrast, both the cereal rye and cereal rye within the mixture had less time to decompose and nitrified N was less susceptible to loss due to spring precipitation. Sampling the cover crop in the fall and again in the spring two weeks before termination, resulted in a significant difference in both total uptake and biomass production between cereal rye and the cereal rye/daikon radish mixture despite the application rate. However, we observed no differences in biomass or total N content between the application rates (200, 145 and 90 kg ha^{-1}) for cereal rye or the mixture. Due to the variable weather conditions experienced over the two year period, N uptake ranged from 32-38 kg ha^{-1}, 35-108 kg ha^{-1} and 31-62 kg ha^{-1}for daikon radish (200 kg ha^{-1} only), cereal rye and the mixture (despite rate), respectively. Within our study, cereal rye demonstrated the ability to sequester the highest N concentration in comparison to daikon radish and the mixture. Under adverse growing conditions, the data suggests these cover crop species have to ability to absorb 15-54% of the fall N in the Upper Mississippi River Basin, assuming a standard range of N rates applied (200-224 kg ha^{-1}).

This study has also established that long-term cover crop integration positively impacts corn uptake at critical growth stages, while demonstrating the capacity to either increase or maintain corn yields. Annual trends demonstrate that in years with large amounts of N being lost (2015), that cover crop inclusion has a greater influence on corn N uptake. Despite year, the addition of the monoculture cover crop species effectively extended uptake potential late into the growing season, increasing the total N content at physiological maturity. On average, at 200 kg N ha^{-1} the addition of cereal rye and daikon radish treatments increased R6 crop uptake by 20%. At R6, we observed significant differences between application rates, 200 kg N ha^{-1}, demonstrated the capacity to increase corn N uptake relative to 145 and 90 kg N ha^{-1}. However, despite rate applied, cereal rye significantly increased total N content at R6, relative to both the control and the cereal rye/daikon radish mixture. In 2014, the absence of a cover crop reduced the crop yielding potential in the initial year for commercial grain by a range of 3-6% relative to cereal rye and the mixture. As a result of the increased yield despite rate, the cover crop treatments demonstrated the potential to reduce the necessary units of N to reach optimum yield and increase overall economic return. Despite weather extremes, the data demonstrated that fall applying N into a living stand of cover crops improved the crop uptake efficiency resulted in equal or greater corn yield.

Multiple years of research have altered the way that producers perceive the use of cover crops. However, there is a need for long-term research to better understand the impact of cover crops and provide data to better educate producers on how to utilize various cover crop species within their current management strategies. As the primary focus has been placed on keeping reactive nitrogen from surface waters, little data has been compiled in order to see if the inclusion of cover crops is an economically feasible option for producers within the MRB. Previously conducted research has proven that cover crops have the potential to help meet long-term nitrogen management and reduction goals as set by the EPA. However, there is also a dearth of knowledge on the efficacy of large scale cover cropping and if the integration of cover crops will satisfy the reduction goals by the specific target date of 2025. Furthermore, if the reduction goals are not meet, how will government agencies respond and will impending regulations be placed on the timing, placement and source of fertilizers used.

APPENDIX A

TABLES AND FIGURES FOR CHAPTER III

Table A-1

Cultural Practices

	Crop Year			
Field Activity	2012	2013	2014	2015
Cover Crop Sampling	Mar. 17	Apr. 7	Apr. 17	Apr.14
Spring Soil Sampling	Mar. 18	Mar. 30	Apr. 18	Apr.16
C. Crop Termination	Mar. 21	Apr. 9	Apr. 18	Apr.17
Tillage	Apr. 3	May.9	May.5	Apr.30
Main Crop Planting	Apr. 23	May.15	May.5	May.2
V6 Crop Sampling	--	--	Jun.9	Jun.11
V12 Crop Sampling	--	--	Jul.1	Jul.3
VT Crop Sampling	--	--	Jul.10	Jul.12
R6 Crop Sampling	--	--	Sep. 16	Sep. 10
Harvest Sampling	Aug. 24	Sep. 14	Sep. 19	Sep.21
Cover Crop Planting	Sep. 13	Sep. 21	Sep. 20	Oct. 1
Fall Soil Sampling	Sep.20	Sep.30	Sep.23	Sep. 29
Cover Crop Sampling	Nov. 27	Nov. 24	Nov.4	Dec. 1
Fall N Fertilizer Date	Nov. 19	Dec. 12	Dec.4	--

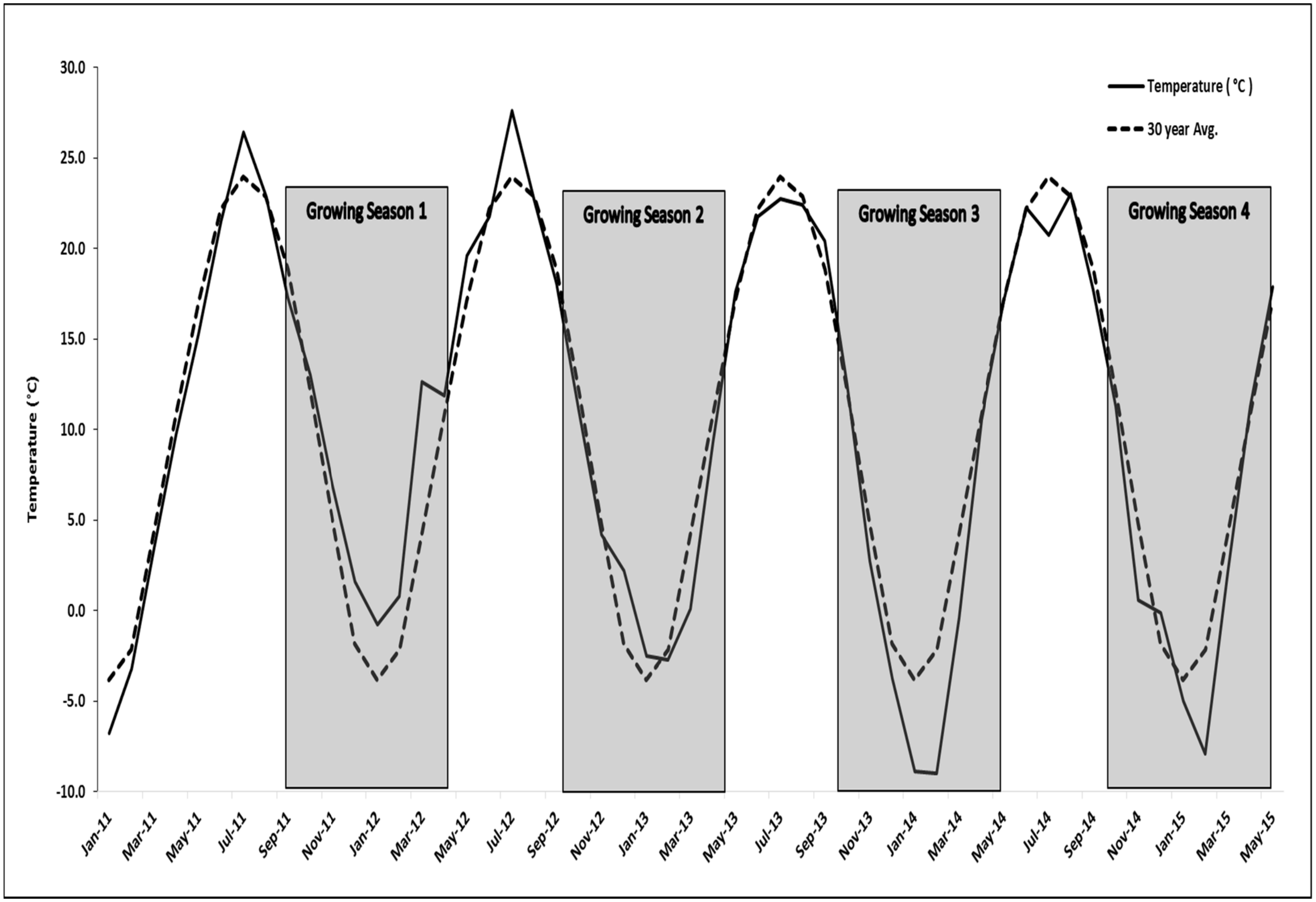

Figure A-1. Ambient air temperature of the 2011-2015 cover crop growing seasons and the 30 year regional averages.

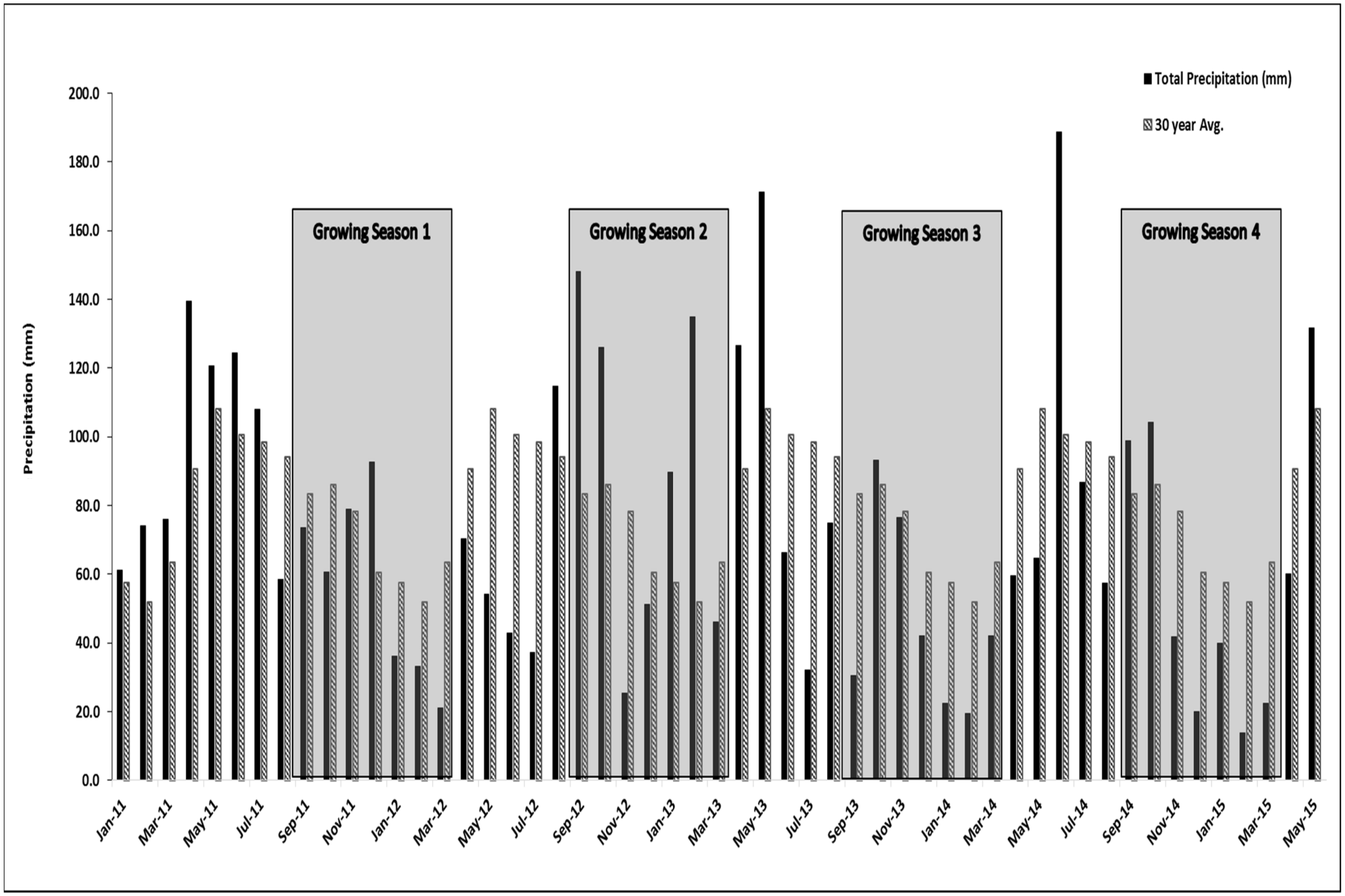

Figure A-2. Average precipitation for the 2011-2015 cover crop growing seasons and the 30 year regional averages.

Table A-2

Cover Crop Growing Degree Days (GDD)

	2011-2012	2012-2013	2013-2014	2014-2015
Fall GDD	1909	1475	1235	1249
Spring GDD	637	370	443	649
Season Total	2547	1845	1679	1898

Table A-3

Cover Crop Biomass Means and Standard Error for 2011-2015 Growing Seasons

Year	Biomass									
	2011-2012		2012-2013		2013-2014		2014-2015		Average	
	kg ha^{-1} / std err									
Daikon Radish	6561.9Aa†	716	3707.5Bb	316.4	1450.3Ac	115.1	638.4Ad	10.75	3089.5A	289.6
Cereal Rye	3906.5Bab	228.4	5585.5Aa	29.8	706.8Ac	108.8	2160Ab	482.2	3089.7A	212.3
Cereal Rye/ Daikon Radish	2363.7Ca	66.4	3348.7Ca	62.6	670.2Ab	179.7	978.3Aab	323.8	1840.2B	158.1

Note: † Uppercase letters indicate significance between treatments within year. Lowercase letters indicate significant differences between years within treatment (a = 0.05).

Table A-4

Cover Crop N Uptake Means and Standard Error for 2011-2015 Growing Seasons

Year	N Uptake									
	2011-2012		2012-2013		2013-2014		2014-2015		Average	
	kg ha^{-1}/ std err									
Daikon Radish	226.8Aa†	22.0	131.9Bb	5.7	38.2Ac	2.7	31.9Bc	1.2	107.2B	7.9
Cereal Rye	188.1ABb	13.4	249.9Aa	3.1	35.0Ad	4.4	107.2Ac	21.8	145.1A	10.7
Cereal Rye/ Daikon Radish	110.6Ba	7.3	128.1Cab	6.5	32.5Ab	7.2	52.3ABb	17.2	80.9C	9.5

Note: † Uppercase letters indicate significance between treatments within year. Lowercase letters indicate significant differences between years within treatment (a = 0.05).

Table A-5

Cover Crop Biomass ANOVA

Source of Variation	DF	F Value	Pr > F
treatment	2	18.38	<.0001
year	3	70.04	<.0001
block	2	0.69	0.5102
treatment*year	6	8.28	<.0001

Note: ANOVA table depicts the response variable (cover crop biomass) and probability values for each source of variation.

Table A-6

Cover Crop N Uptake ANOVA

Source of Variation	DF	F Value	Pr > F
treatment	2	39.47	<.0001
year	3	95.91	<.0001
block	2	0.3	0.7463
treatment*year	6	15.41	<.0001

Note: ANOVA table depicts the response variable (cover crop N uptake) and probability values for each source of variation.

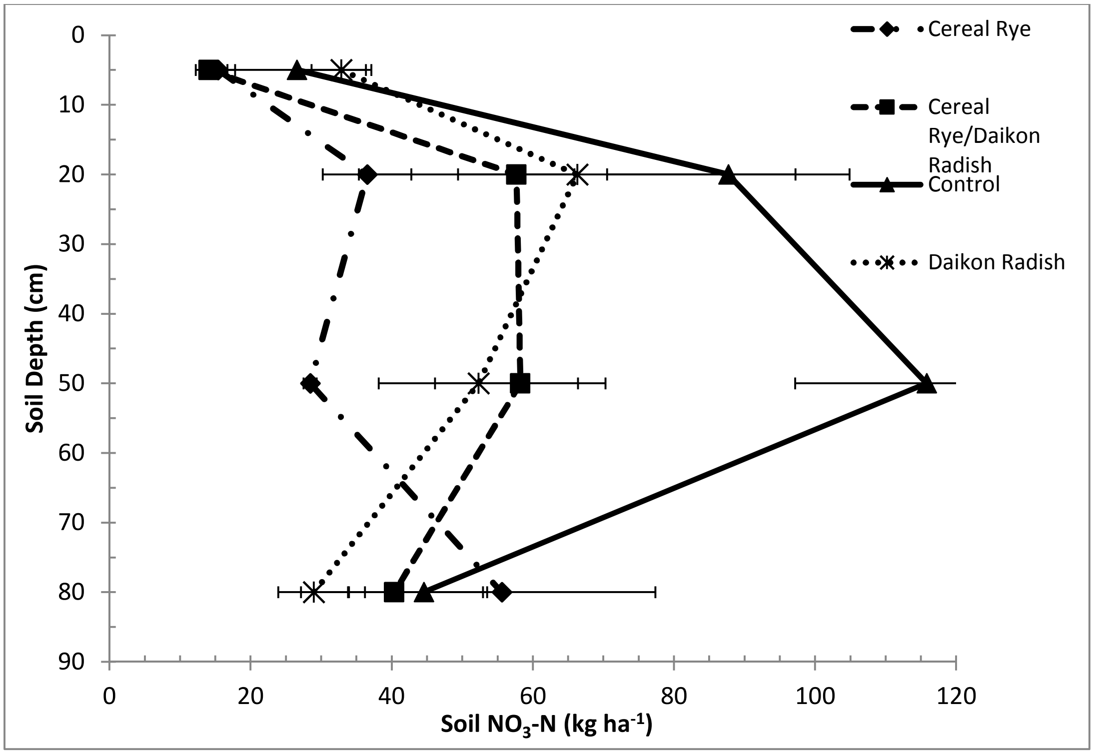

Figure A-3. Soil nitrate (kg N ha^{-1}) by depth (cm) collected in spring of 2012.

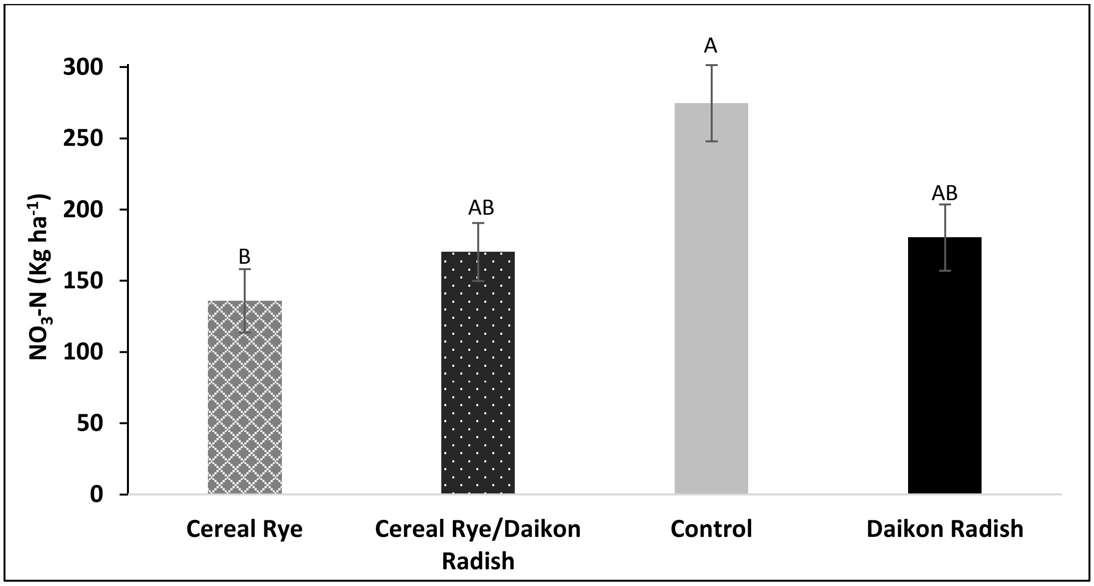

Figure A-4. Soil nitrate (kg N ha^{-1}) by treatment. Samples collected in the spring of 2012. Different letters indicate significant difference at an alpha level of 0.05.

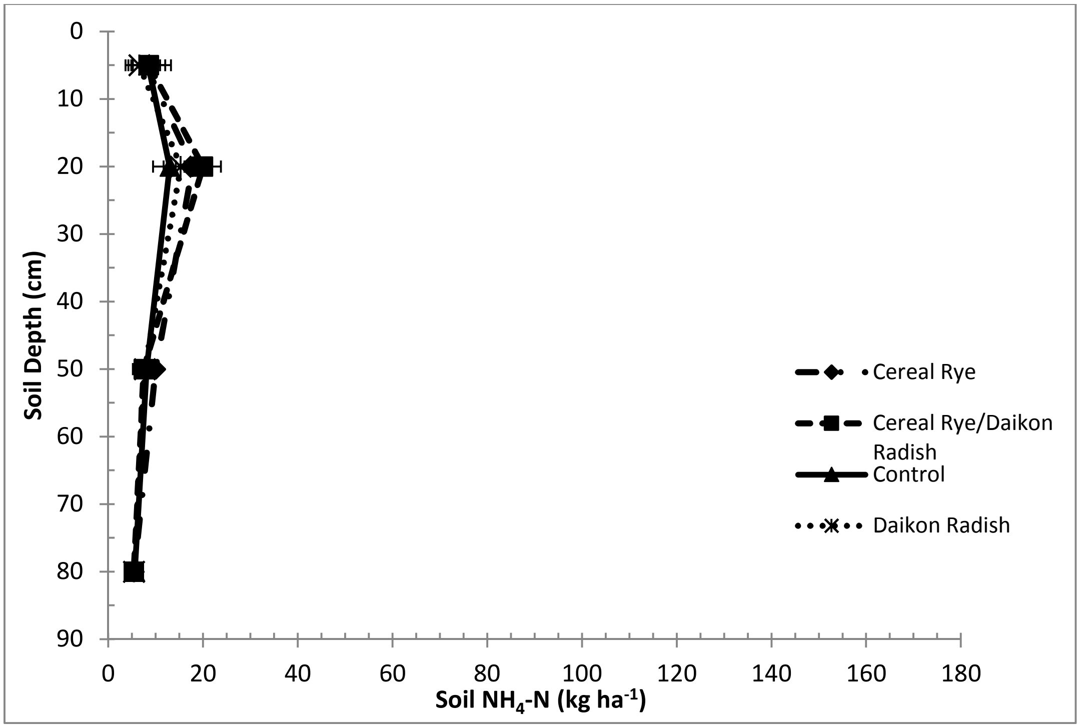

Figure A-5. Soil ammonium (kg N ha^{-1}) by depth (cm) collected in spring of 2012.

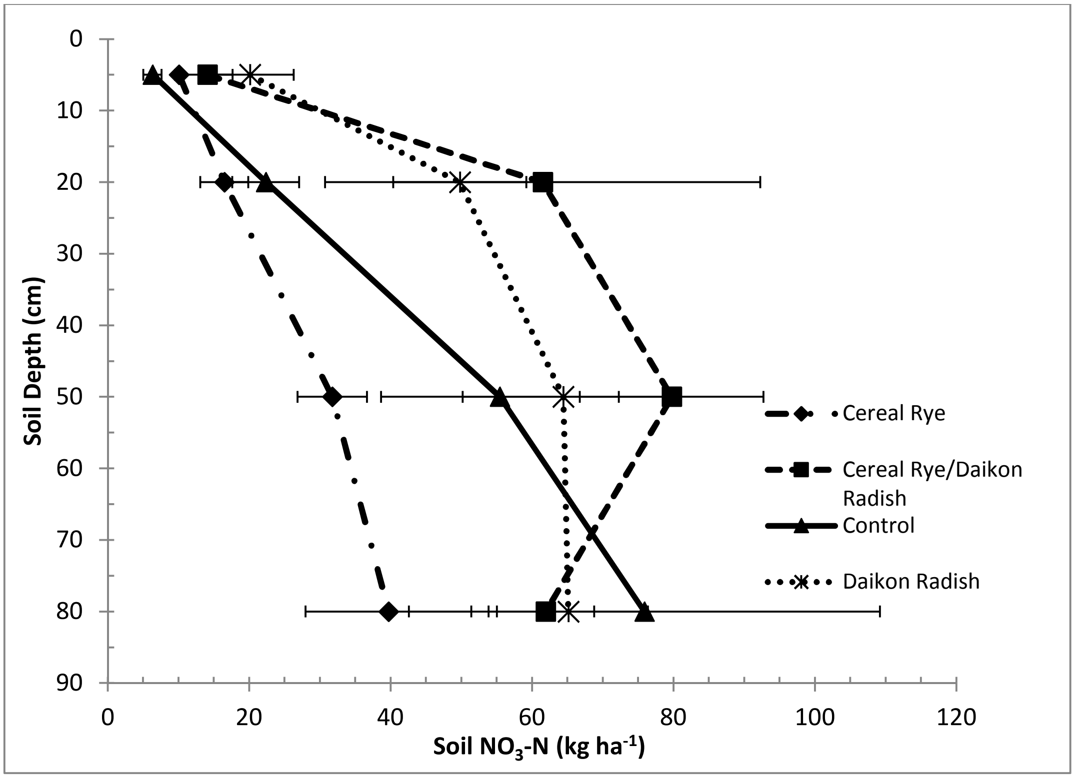

Figure A-6. Soil nitrate (kg N ha^{-1}) by depth (cm) collected in spring of 2013.

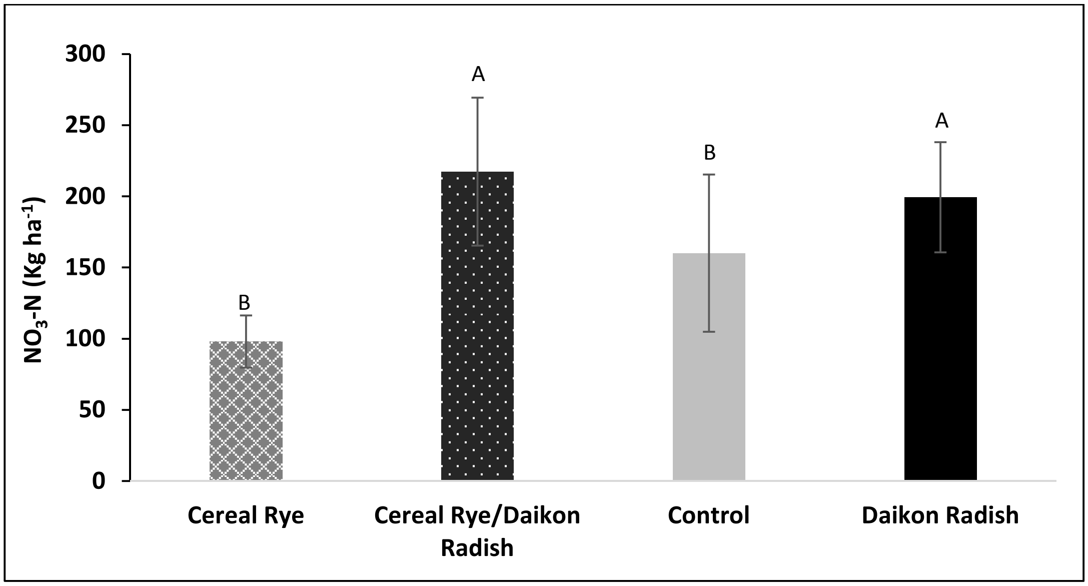

Figure A-7. Soil nitrate (kg N ha^{-1}) by treatment. Samples collected in the spring of 2013. Different letters indicate significant difference at an alpha level

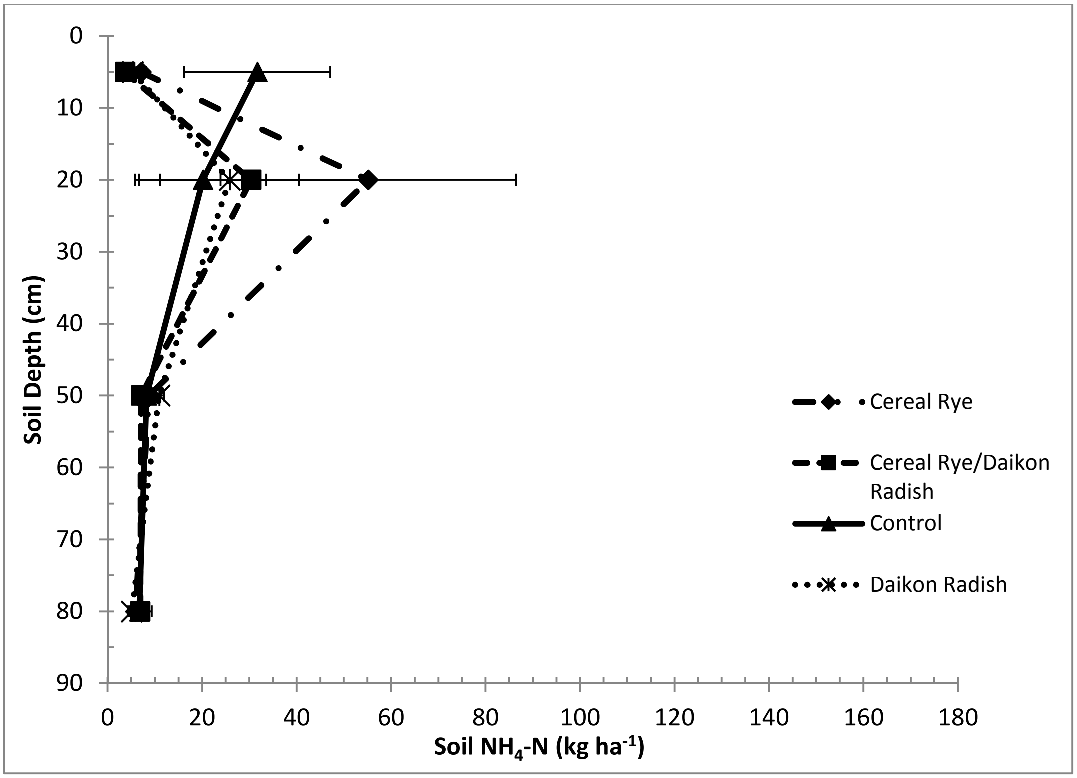

Figure A-8. Soil ammonium (kg N ha^{-1}) by depth (cm) collected in spring of 2013.

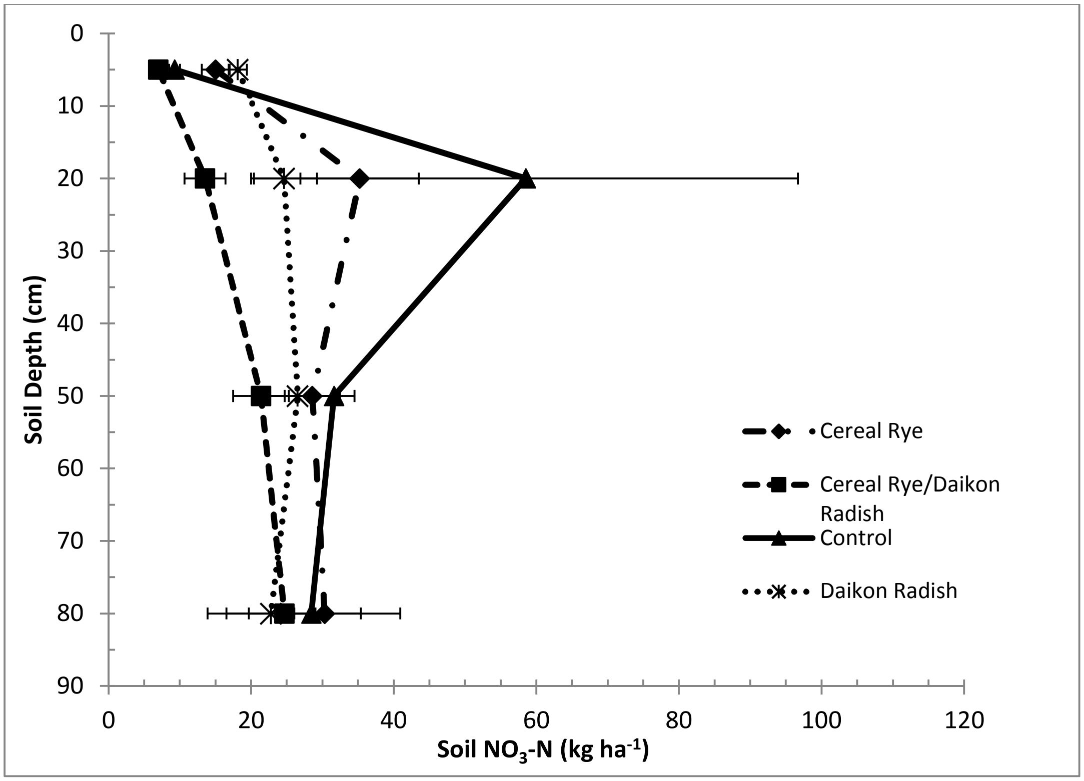

Figure A-9. Soil nitrate (kg N ha^{-1}) by depth (cm) collected in spring of 2014.

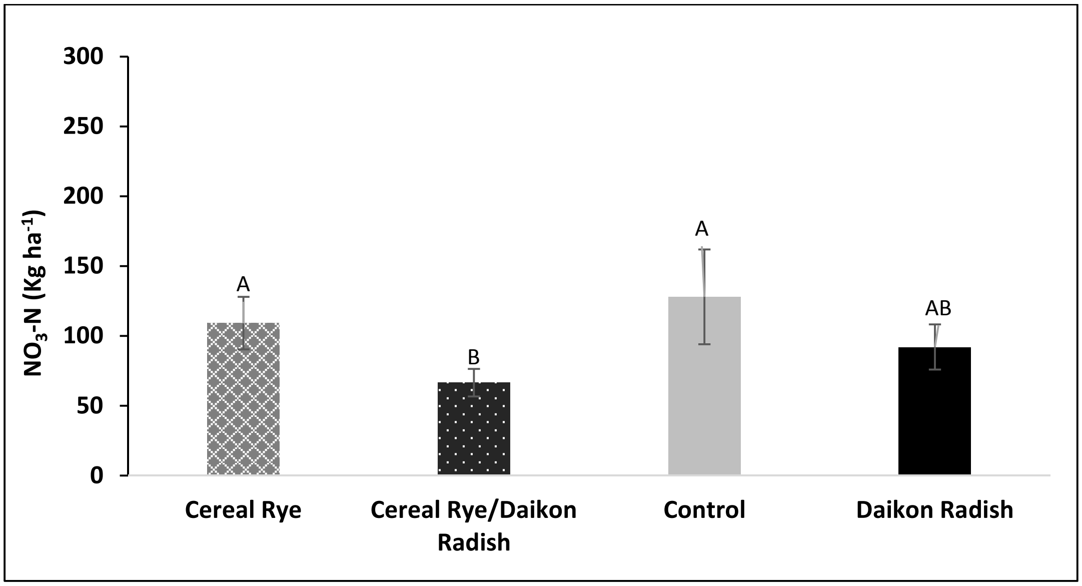

Figure A-10. Soil nitrate (kg N ha^{-1}) by treatment. Samples collected in the spring of 2014. Different letters indicate significant difference at an alpha level of 0.05.

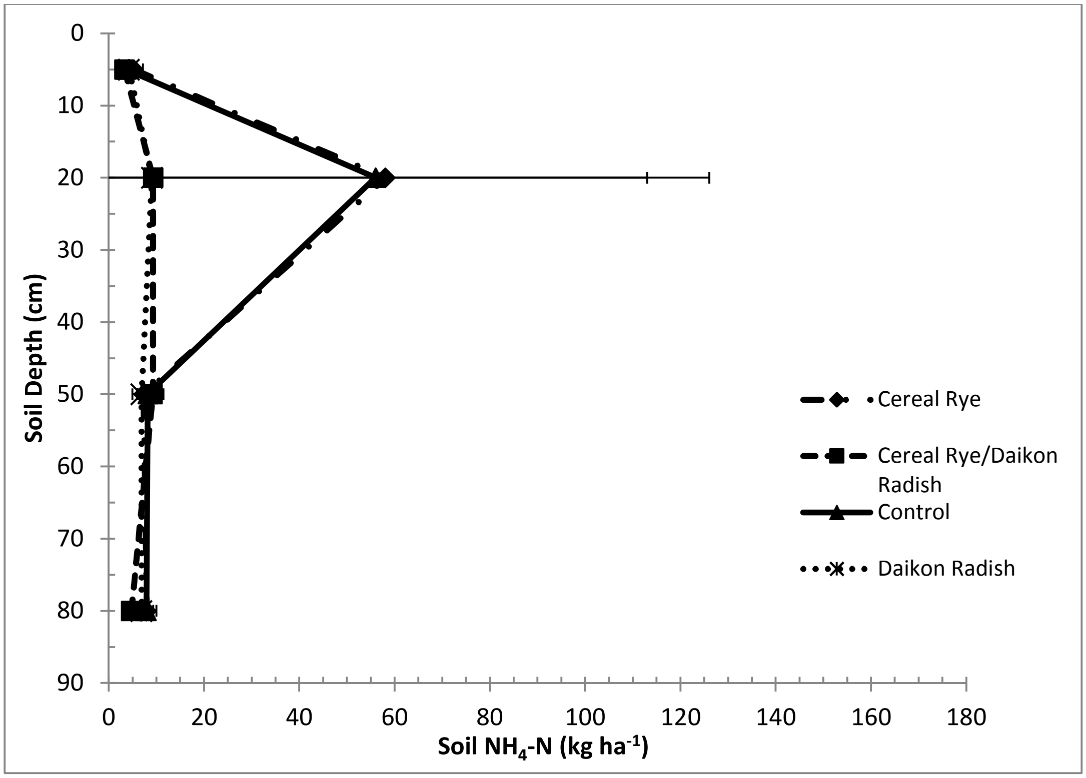

Figure A-11. Soil ammonium (kg N ha^{-1}) by depth (cm) collected in spring of 2014.

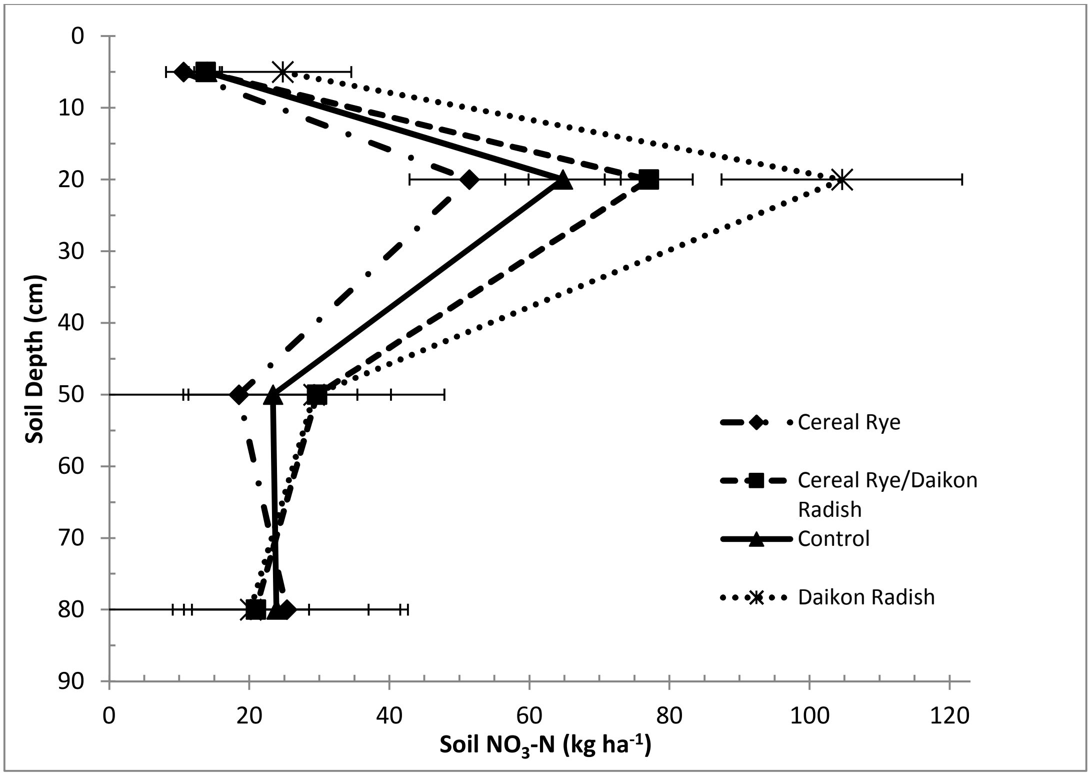

Figure A-12. Soil nitrate (kg N ha^{-1}) by depth (cm) collected in spring of 2015.

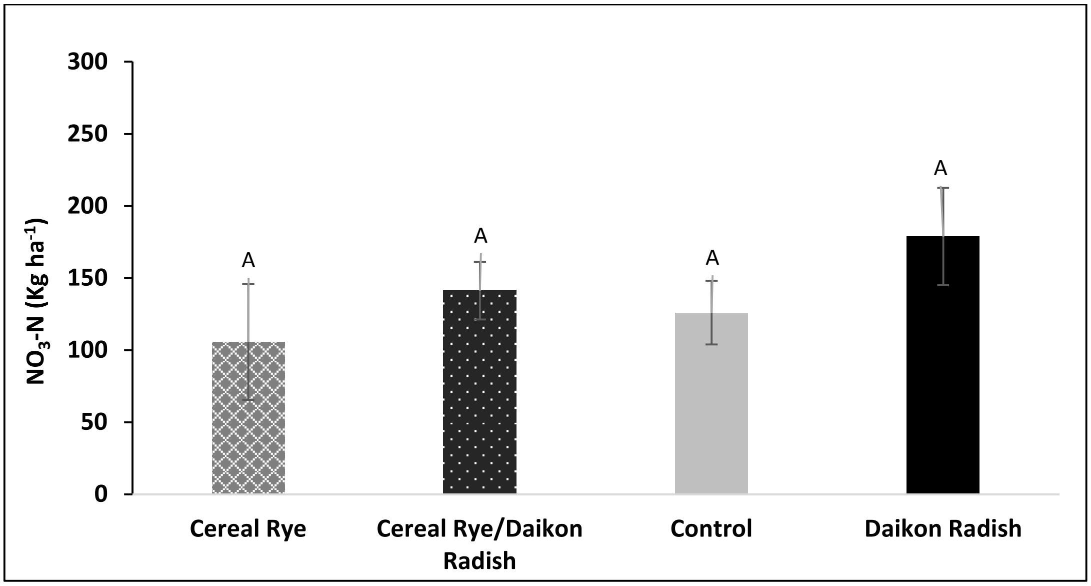

Figure A-13. Soil nitrate (kg N ha^{-1}) by treatment. Samples collected in the spring of 2015. Different letters indicate significant difference at an alpha level of 0.05.

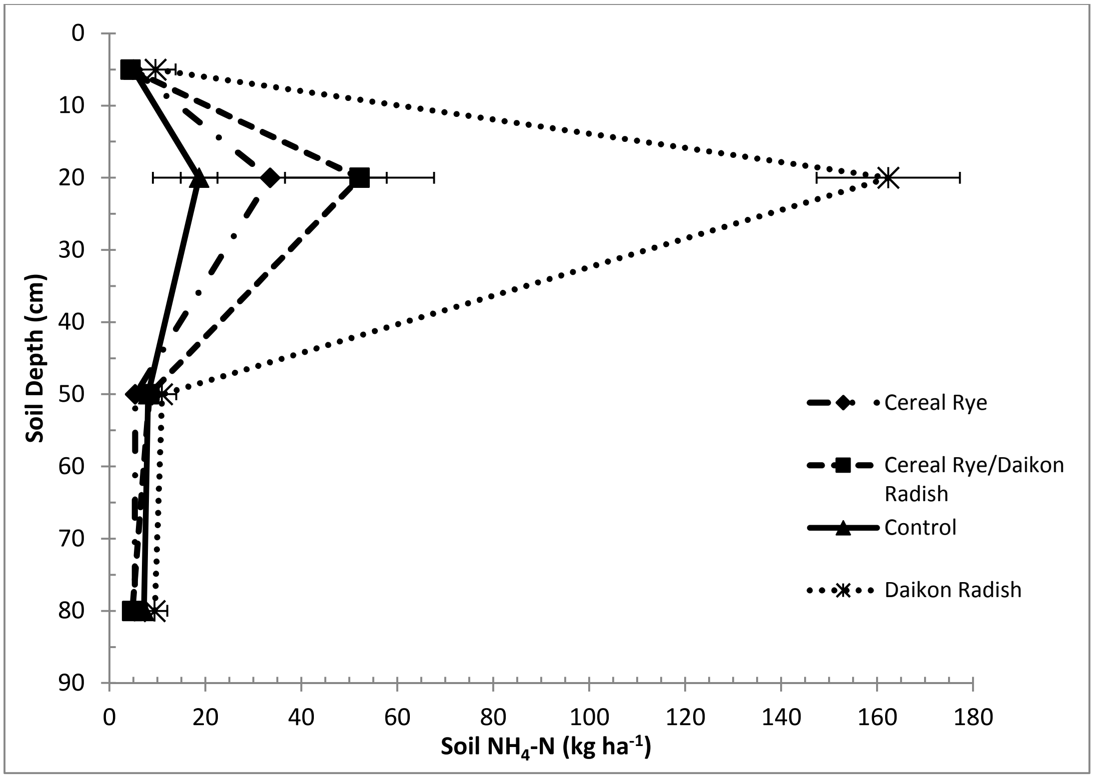

Figure A-14. Soil ammonium (kg N ha^{-1}) by depth (cm) collected in the spring of 2015.

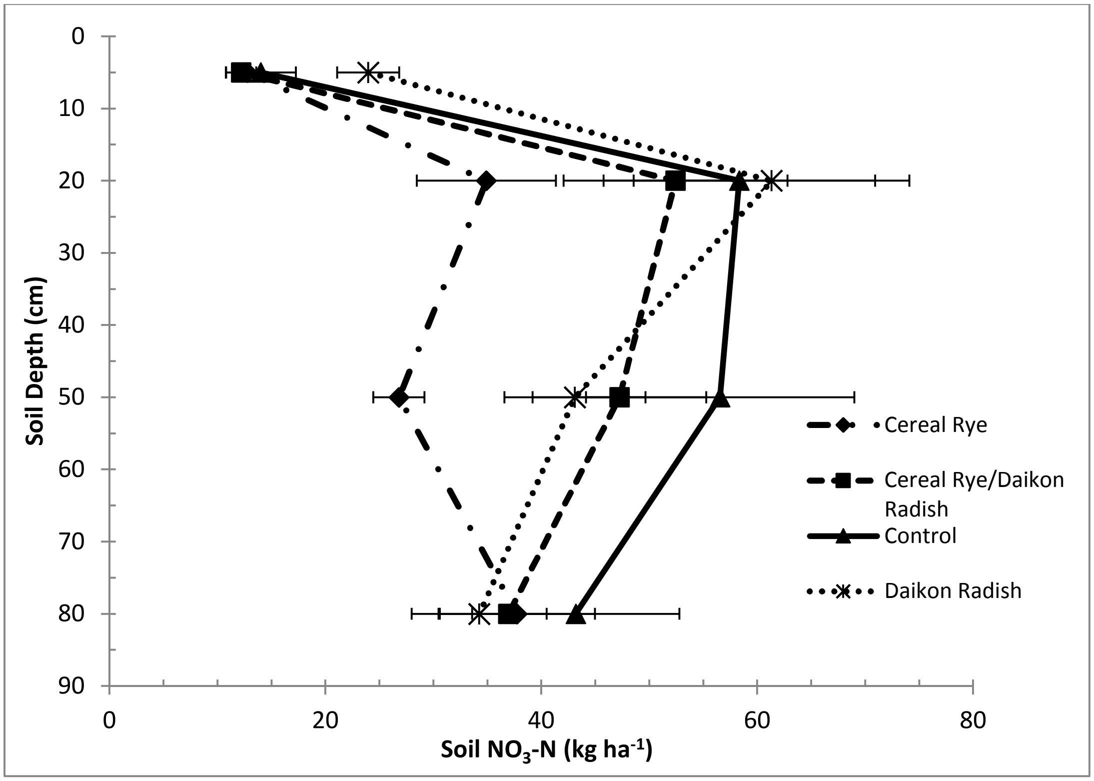

Figure A-15. Average soil nitrate (kg N ha^{-1}) by depth (cm). Samples collected in spring of each season (2011-2015).

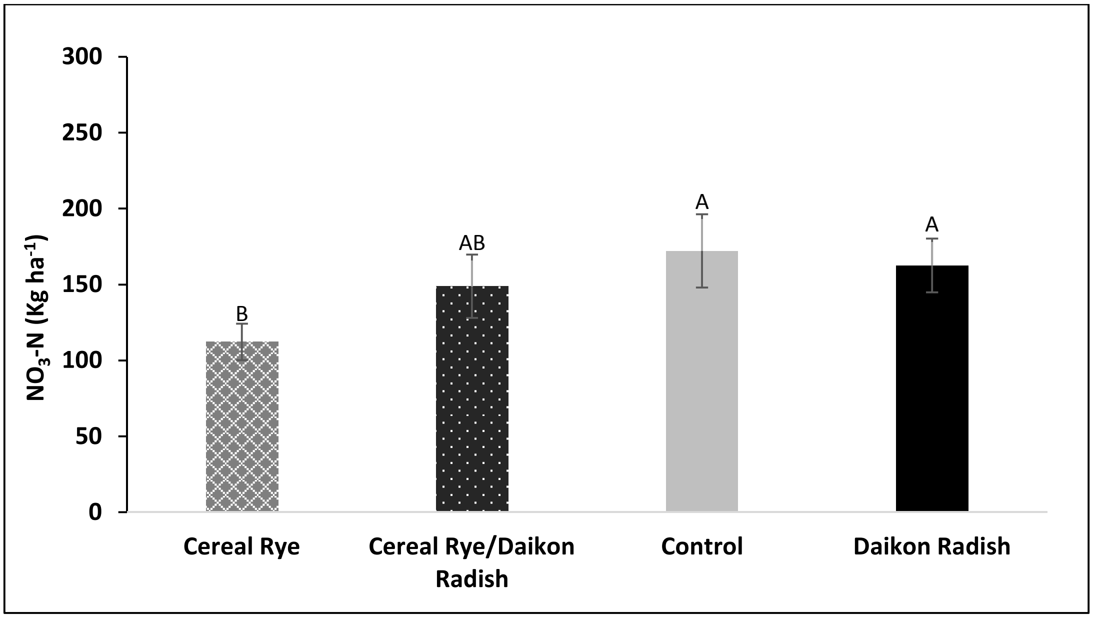

Figure A-16. Average soil nitrate (kg N ha^{-1}) by treatment. Samples collected in the spring of each season (2011-2015). Different letters indicate significant difference at an alpha level of 0.05.

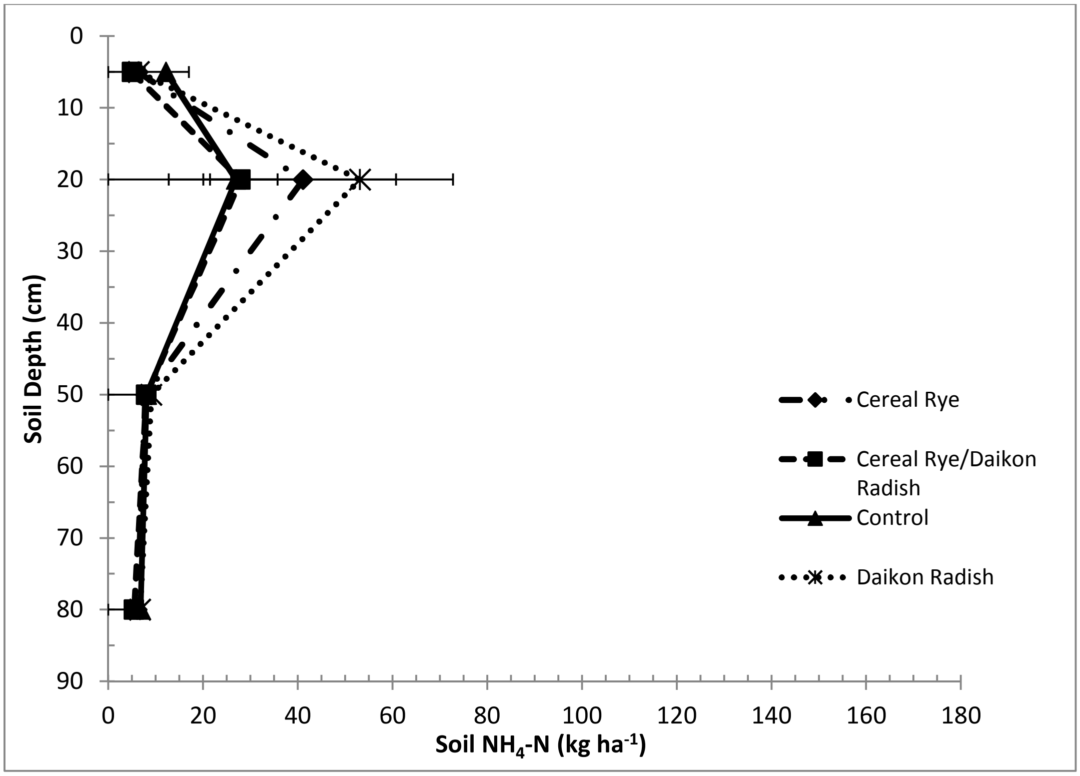

Figure A-17. Average soil ammonium (kg N ha^{-1}) by depth (cm) collected in the spring of each season (2011-2015).

Table A-7

Soil Distribution (NO_3-N) ANOVA

Source of Variation	DF	F Value	Pr > F
treatment	3	4.15	0.0077
year	3	9.43	<.0001
depth	3	22.75	<.0001
block	2	1.18	0.3115
treatment*year	9	2.58	0.0091
treatment*depth	9	1.33	0.2283
year*depth	9	5.8	<.0001
treatment*year*depth	27	1.01	0.4577

Note: ANOVA table depicts the response variable (NO_3-N distribution) and probability values for each source of variation.

Table A-8

Soil Distribution (NH_4-N) ANOVA

Source of Variation	DF	F Value	Pr > F
treatment	3	0.22	0.885
year	3	1.8	0.1506
depth	3	2.71	0.048
block	2	2.9	0.0585
treatment*year	9	1.48	0.1622
treatment*depth	9	0.27	0.9811
year*depth	9	1.62	0.1173
treatment*year*depth	27	0.82	0.7163

Note: ANOVA table depicts the response variable (NH_4-N distribution) and probability values for each source of variation.

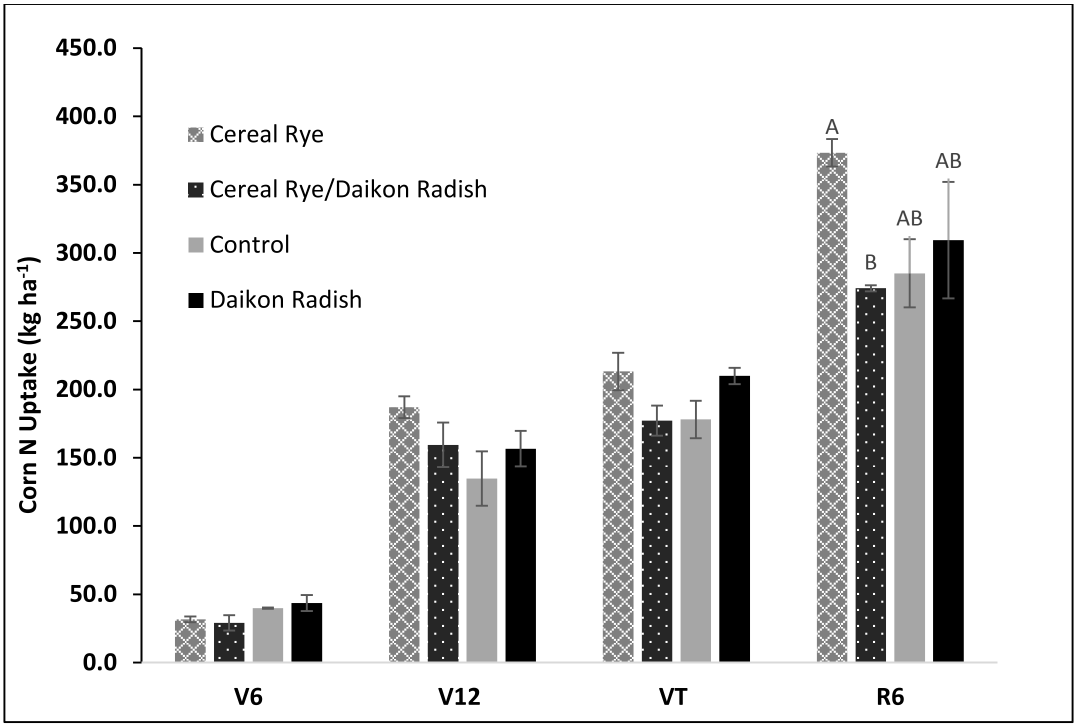

Figure A-18. Crop N uptake (kg ha^{-1}) by growth stage. Samples collected throughout the 2014 corn growing season. Different letters indicate significant difference at individual growth stages. (Alpha level of 0.05).

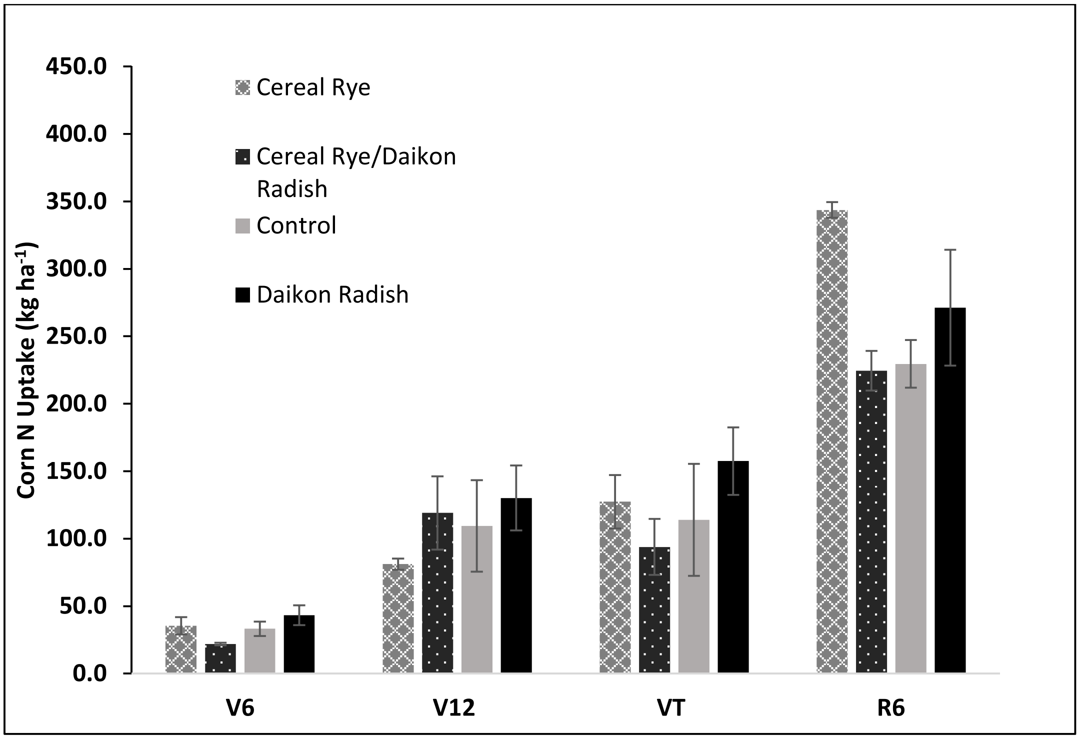

Figure A-19. Crop N uptake (kg ha^{-1}) by growth stage. Samples collected throughout the 2015 corn growing season.

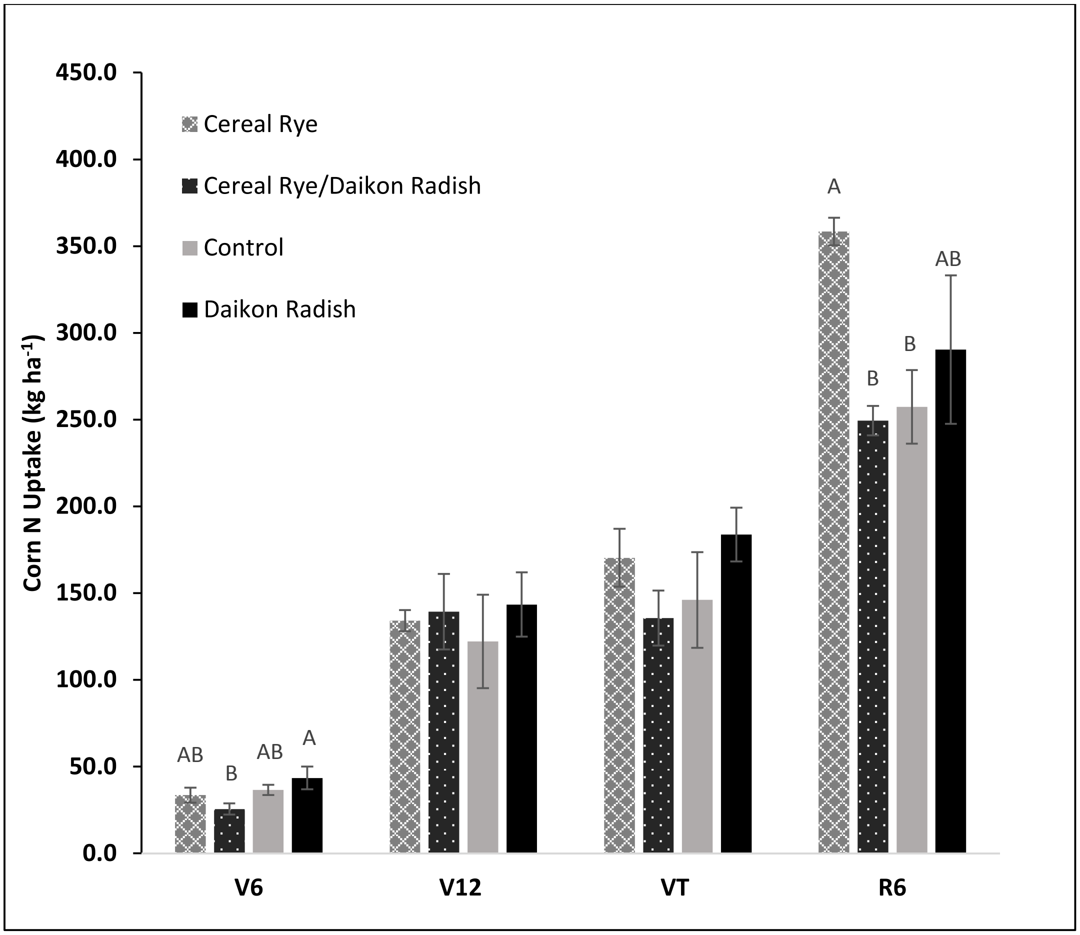

Figure A-20. Average crop N uptake (kg ha^{-1}) by growth stage (2014-2015). Samples collected throughout both corn growing season. Different letters indicate significant difference at individual growth stages. (Alpha level of 0.05). No significant differences at V12 or VT.

Table A-9

Crop Uptake (V6) ANOVA (2013-2015)

Source of Variation	DF	F Value	Pr > F
treatment	3	4.58	0.0196
year	1	0.57	0.4636
block	2	1.14	0.3479
treatment*year	3	0.58	0.6386

Note: ANOVA table depicts the response variable (V6 crop uptake) and probability values for each source of variation.

Table A-10

Crop Uptake (V12) ANOVA (2013-2015)

Source of Variation	DF	F Value	Pr > F
treatment	3	0.38	0.7661
year	1	11.04	0.005
block	2	0.59	0.5674
treatment*year	3	1.64	0.2254

Note: ANOVA table depicts the response variable (V12 crop uptake) and probability values for each source of variation.

Table A-11

Crop Uptake (VT) ANOVA (2013-2015)

Source of Variation	DF	F Value	Pr > F
treatment	3	1.89	0.1779
year	1	19.83	0.0005
block	2	0.2	0.8172
treatment*year	3	0.25	0.8612

Note: ANOVA table depicts the response variable (VT crop uptake) and probability values for each source of variation.

Table A-12

Crop Uptake (R6) ANOVA (2013-2015)

Source of Variation	DF	F Value	Pr > F
treatment	3	8	0.0024
year	1	6.06	0.0275
block	2	1.02	0.3866
treatment*year	3	0.11	0.9532

Note: ANOVA table depicts the response variable (R6 crop uptake) and probability values for each source of variation.

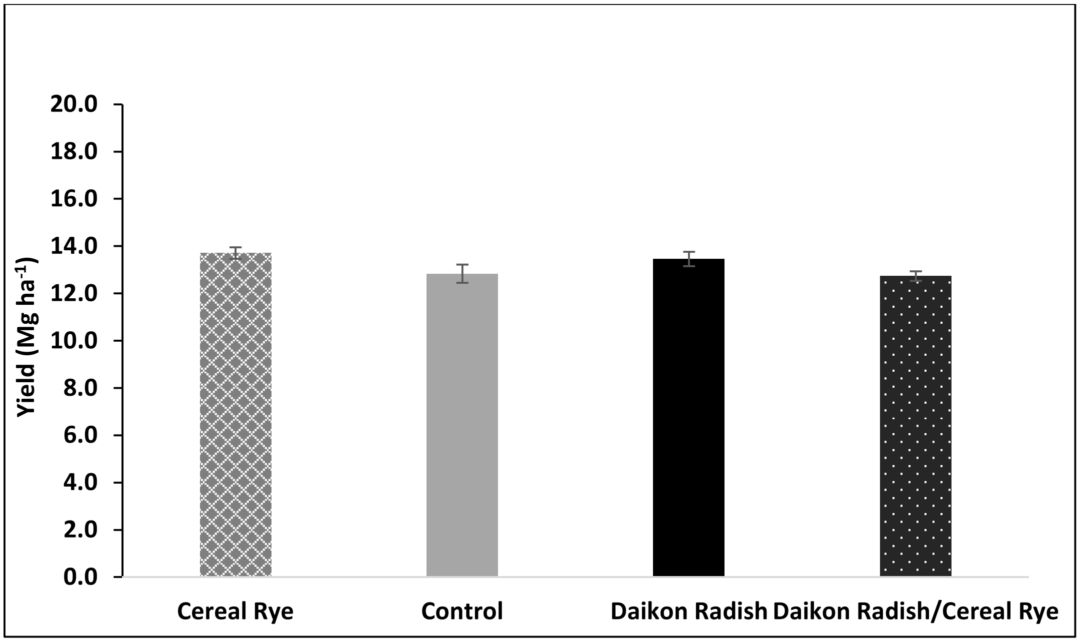

Figure A-21. Corn yield (Mg ha^{-1}) by treatment. Samples collected at harvest (2014). No significant differences between treatment yield at 200 kg N ha^{-1}.

Table A-13

2014 Grain Yield ANOVA

Source of Variation	DF	F Value	Pr > F
treatment	3	2.15	0.1946
block	2	0.23	0.804

Note: ANOVA table depicts the response variable (grain yield) and probability values for each source of variation.

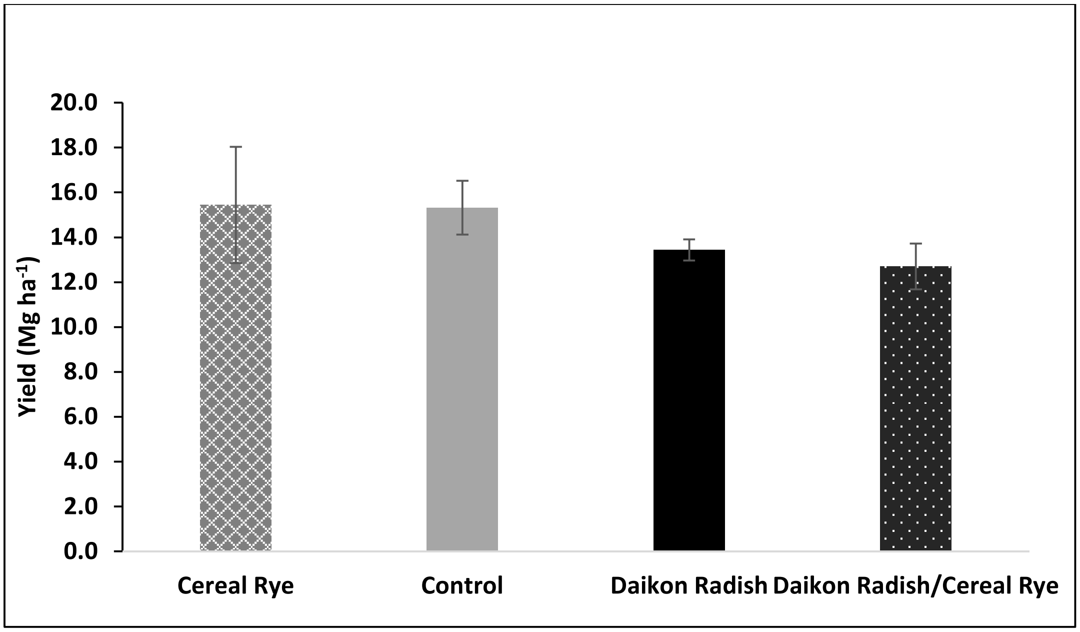

Figure A-22. Corn yield (Mg ha^{-1}) by treatment. Samples collected at harvest (2015). No significant differences between treatment yield at 200 kg N ha^{-1}.

Table A-14

2015 Grain Yield ANOVA

Source of Variation	DF	F Value	Pr > F
treatment	3	0.8	0.536
block	2	1.04	0.4084

Note: ANOVA table depicts the response variable (grain yield) and probability values for each source of variation.

APPENDIX B

TABLES AND FIGURES FOR CHAPTER IV

Table B-1

Cultural Practices

	Crop Year			
Field Activity	2012	2013	2014	2015
Cover Crop Sampling	Mar. 17	Apr. 7	Apr. 17	Apr.14
C. Crop Termination	Mar. 21	Apr. 9	Apr. 18	Apr.17
Tillage	Apr. 3	May.9	May.5	Apr.30
Main Crop Planting	Apr. 23	May.15	May.5	May.2
V6 Crop Sampling	--	--	Jun.9	Jun.11
V12 Crop Sampling	--	--	Jul.1	Jul.3
VT Crop Sampling	--	--	Jul.10	Jul.12
R6 Crop Sampling	--	--	Sep. 16	Sep. 10
Harvest Sampling	Aug. 24	Sep. 14	Sep. 19	Sep.21
Cover Crop Planting	Sep. 13	Sep. 21	Sep. 20	Oct. 1
Cover Crop Sampling	Nov. 27	Nov. 24	Nov.4	Dec. 1
Fall N Fertilizer Date	Nov. 19	Dec. 12	Dec.4	--

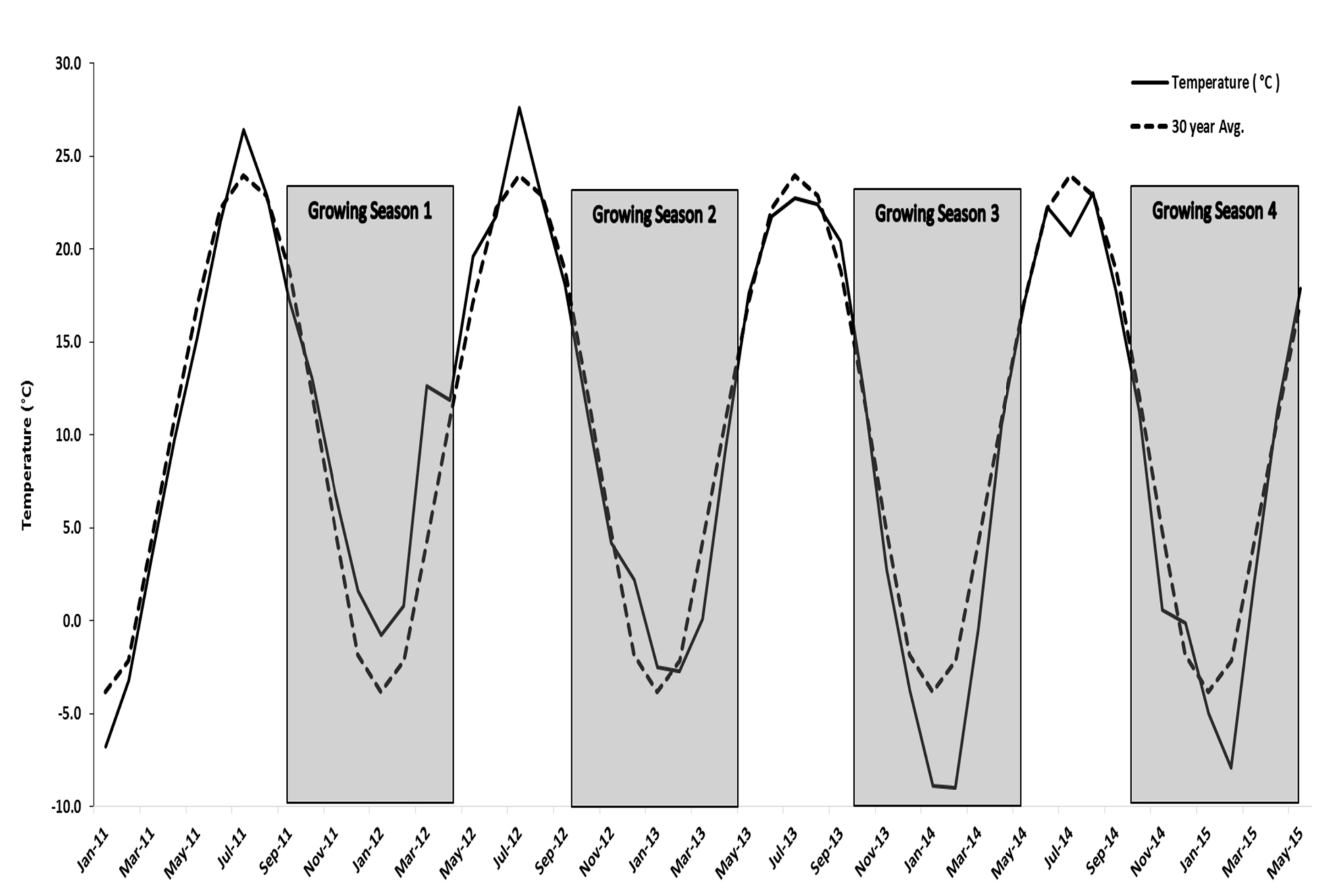

Figure B-1. Ambient air temperature of the 2011-2015 cover crop growing seasons and the 30 year regional averages.

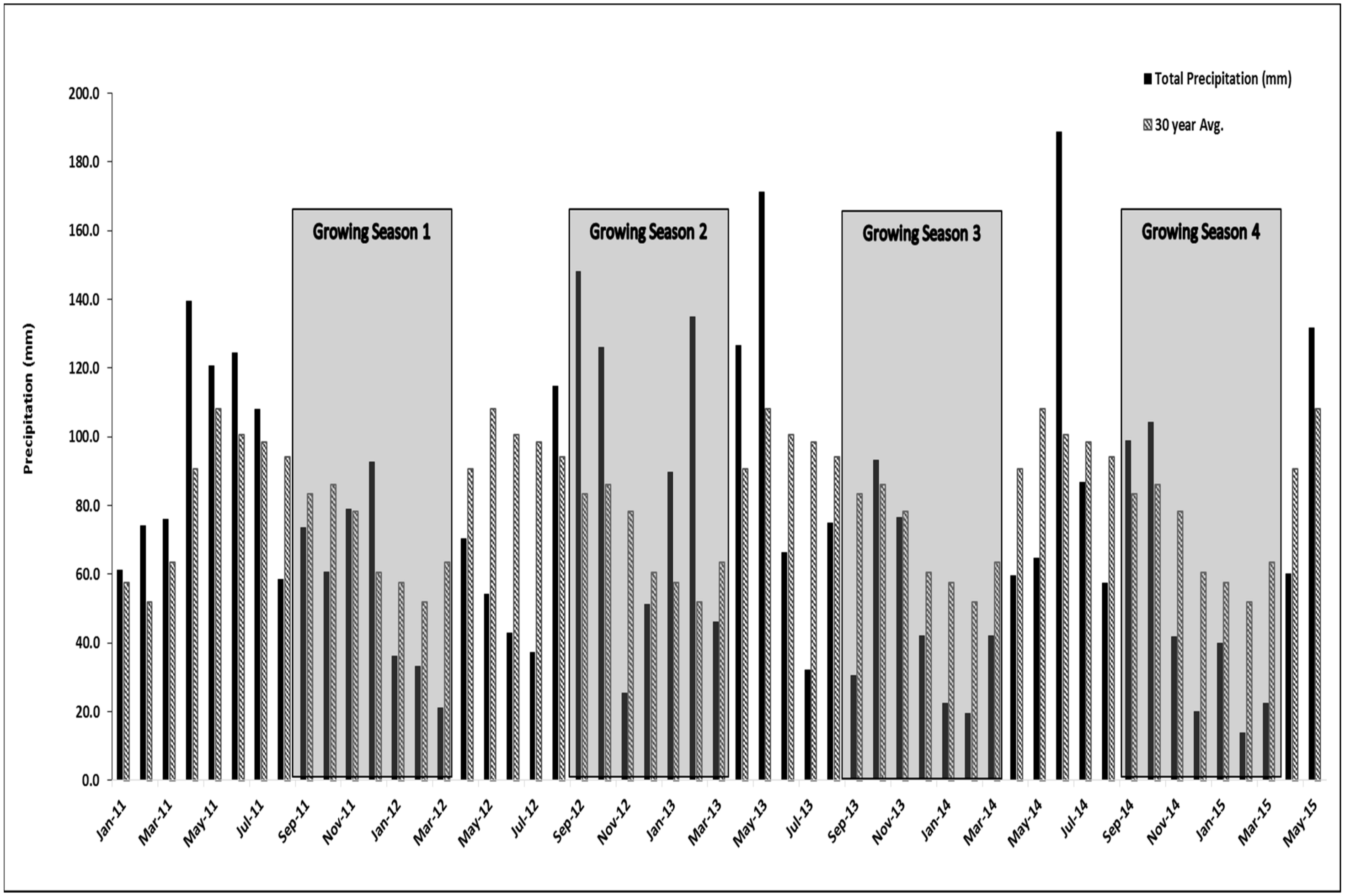

Figure B-2. Average precipitation for the 2011-2015 cover crop growing seasons and the 30 year regional averages.

Table B-2

Cover Crop Growing Degree Days (GDD)

	2013-2014	2014-2015
Fall GDD	1235	1249
Spring GDD	443	649
Season Total	1679	1898

Table B-3

Cover Crop Biomass Means and Standard Error (200 kg N ha^{-1}) for 2013-2015 Growing Seasons

Year	Biomass					
	2013-2014		2014-2015		Average	
	kg ha^{-1}	std err	kg ha^{-1}	std err	kg ha^{-1}	std err
Daikon Radish	1450.3Aa†	115.1	638.4Ba	10.75	1044.4A	62.9
Cereal Rye	706.8Ab	108.8	2160Aa	482.2	1433.4A	295.5
Cereal Rye/ Daikon Radish	670.2Aa	179.7	978.3Aba	323.8	842.2A	251.8

Note: † Uppercase letters indicate significance between treatments within year. Lowercase letters indicate significant differences between years within treatment (a = 0.05).

Table B-4

Cover Crop N Uptake Means and Standard Error (200 kg N ha^{-1}) for 2013-2015 Growing Seasons

Year	N Uptake					
	2013-2014		2014-2015		Average	
	kg ha^{-1}	std err	kg ha^{-1}	std err	kg ha^{-1}	std err
Daikon Radish	38.2Aa†	2.7	31.9Ba	1.2	35.0B	2.0
Cereal Rye	35.0Ab	4.4	107.2Aa	21.8	71.2A	13.1
Cereal Rye/ Daikon Radish	32.5Aa	7.2	52.3Aba	17.2	42.4AB	12.2

Note: † Uppercase letters indicate significance between treatments within year. Lowercase letters indicate significant differences between years within treatment (a = 0.05).

Table B-5

Cover Crop Biomass (200 kg N ha^{-1}) ANOVA (2013-2015)

Source of Variation	DF	F Value	Pr > F
treatment	2	2.43	0.1376
year	1	1.92	0.1958
block	2	0.05	0.9497
treatment*year	2	8.21	0.0078

Note: ANOVA table depicts the response variable (cover crop biomass) and probability values for each source of variation.

Table B-6

Cover Crop N Uptake (200 kg N ha^{-1}) ANOVA (2013-2015)

Source of Variation	DF	F Value	Pr > F
treatment	2	4.32	0.0445
year	1	7.26	0.0225
block	2	0.04	0.9631
treatment*year	2	4.73	0.0358

Note: ANOVA table depicts the response variable (cover crop N uptake) and probability values for each source of variation.

Table B-7

Cover Crop Biomass Means and Standard Error by Rate for 2013-2015 Growing Seasons

Year	Biomass													
	2013-2014						2014-2015						Average	
	kg ha^{-1} / std err													
	90 kg N ha^{-1}		145 kg N ha^{-1}		200 kg N ha^{-1}		90 kg N ha^{-1}		145 kg N ha^{-1}		200 kg N ha^{-1}		Average	
Cereal Rye	798.9 Ab†	63.7	809.3 Ab	133.9	706.8 Ab	108.8	2089.8 Aa	160.1	2447.0 Aa	73.9	2160 Aa	482.2	1502.0 A	170.4
Cereal Rye/ Daikon Radish	586.0 Aa	69.7	657.8 Aa	105.8	670.2 Aa	179.7	1312.0 Aa	360.3	1259.0 Aa	242.4	978.3 Aa	323.8	910.5 B	213.6

Note. †Uppercase letters indicate significance between treatments within year. Lowercase letters indicate significant differences between years within treatment (a = 0.05).

Table B-8

Cover Crop N Uptake Means and Standard Error by Rate for 2013-2015 Growing Seasons

Year	N Uptake													
	2013-2014						2014-2015						Average	
	kg ha^{-1} / std err													
	90 kg N ha^{-1}		145 kg N ha^{-1}		200 kg N ha^{-1}		90 kg N ha^{-1}		145 kg N ha^{-1}		200 kg N ha^{-1}		Average	
Cereal Rye	36.1 Ab†	1.7	36.2 Ab	3.7	35.0 Ab	4.4	104.4 Aa	9.0	112.6 Aa	4.0	107.2 Aa	21.8	71.9 A	7.4
Cereal Rye/ Daikon Radish	28.4 Aa	2.4	32.1 Aa	3.7	32.5 Aa	7.2	67.5 Aa	18.8	65.5 Aa	12.9	52.3 Aa	17.2	46.4A	10.4

Note. † Uppercase letters indicate significance between treatments within year. Lowercase letters indicate significant differences between years within treatment (a = 0.05).

Table B-9

Cover Crop Biomass (by rate) ANOVA (2013-2015)

Source of Variation	DF	F Value	Pr > F
treatment	1	18.18	0.0003
year	1	52.27	<.0001
rate	2	0.47	0.6291
block	2	0.07	0.9289
treatment*year	1	10.89	0.0033
treatment*rate	2	0.14	0.8737
year*rate	2	0.25	0.783
treatment*year*rate	2	0.41	0.6674

Note: ANOVA table depicts the response variable (cover crop biomass) and probability values for each source of variation.

Table B-10

Cover Crop N Uptake (by rate) ANOVA (2013-2015)

Source of Variation	DF	F Value	Pr > F
treatment	1	14.73	0.0009
year	1	59.9	<.0001
rate	2	0.17	0.8409
block	2	0.23	0.7995
treatment*year	1	9.74	0.005
treatment*rate	2	0.08	0.9249
year*rate	2	0.18	0.8403
treatment*year*rate	2	0.26	0.7771

Note: ANOVA table depicts the response variable (cover crop N uptake) and probability values for each source of variation.

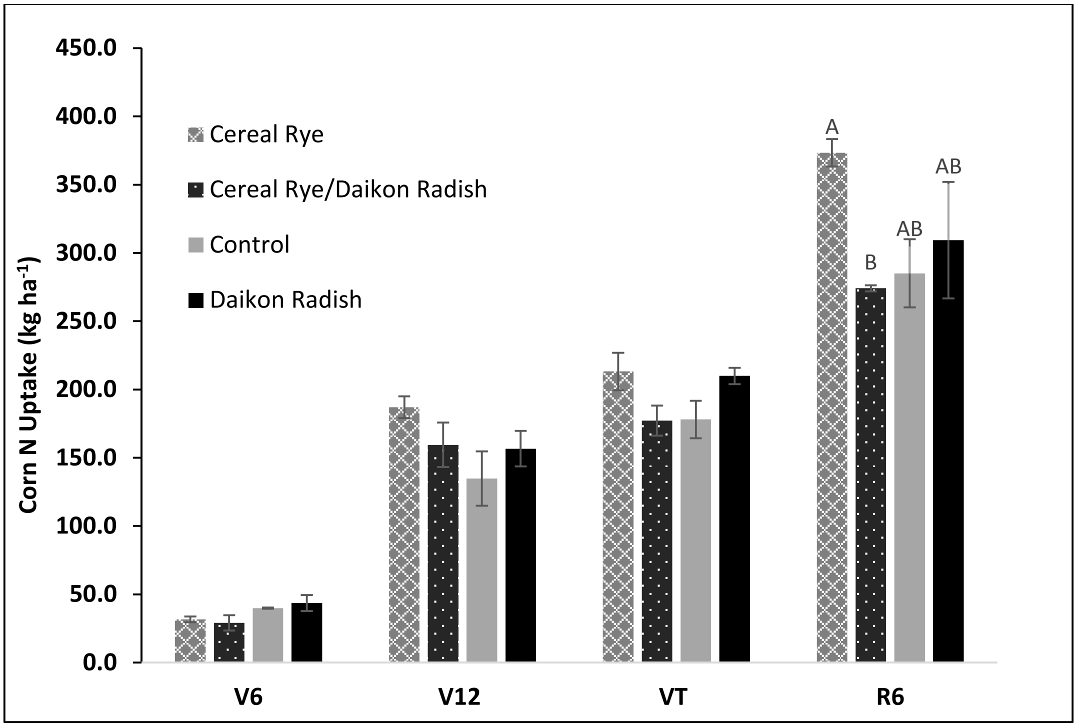

Figure B-3. Crop N uptake (kg ha^{-1}) at 200 kg N ha^{-1} by growth stage. Samples collected throughout the 2014 corn growing season. Different letters indicate significant difference at individual growth stages (Alpha level of 0.05).

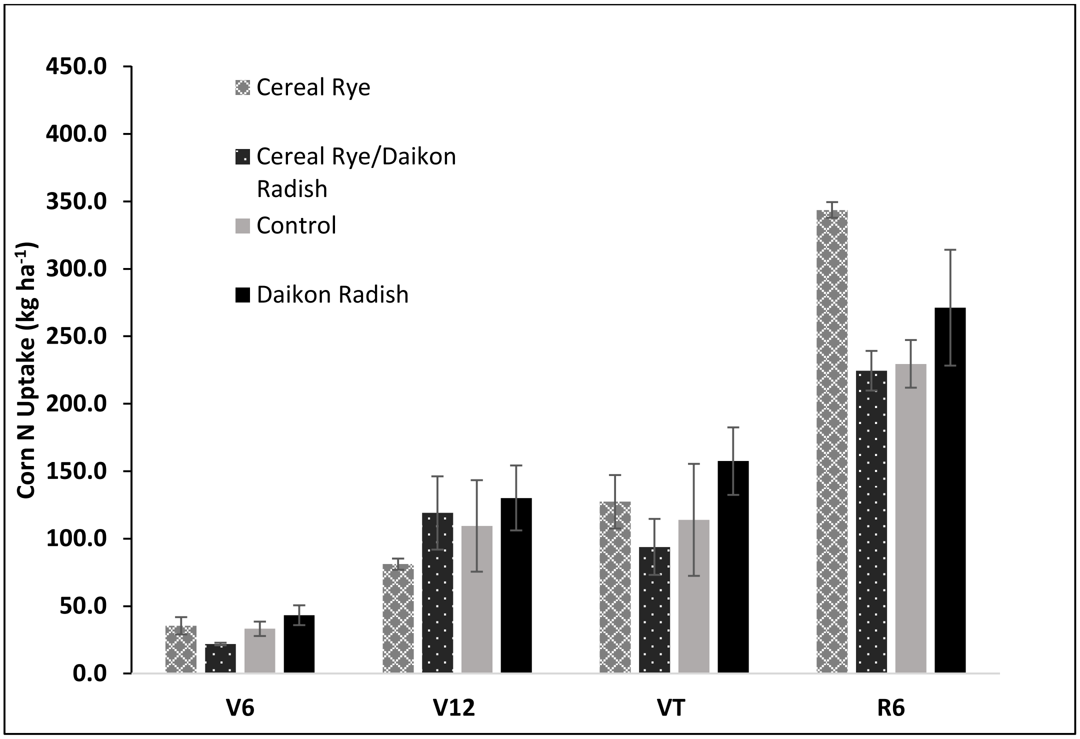

Figure B-4. Crop N uptake (kg ha^{-1}) at 200 kg N ha^{-1} by growth stage. Samples collected throughout the 2015 corn growing season.

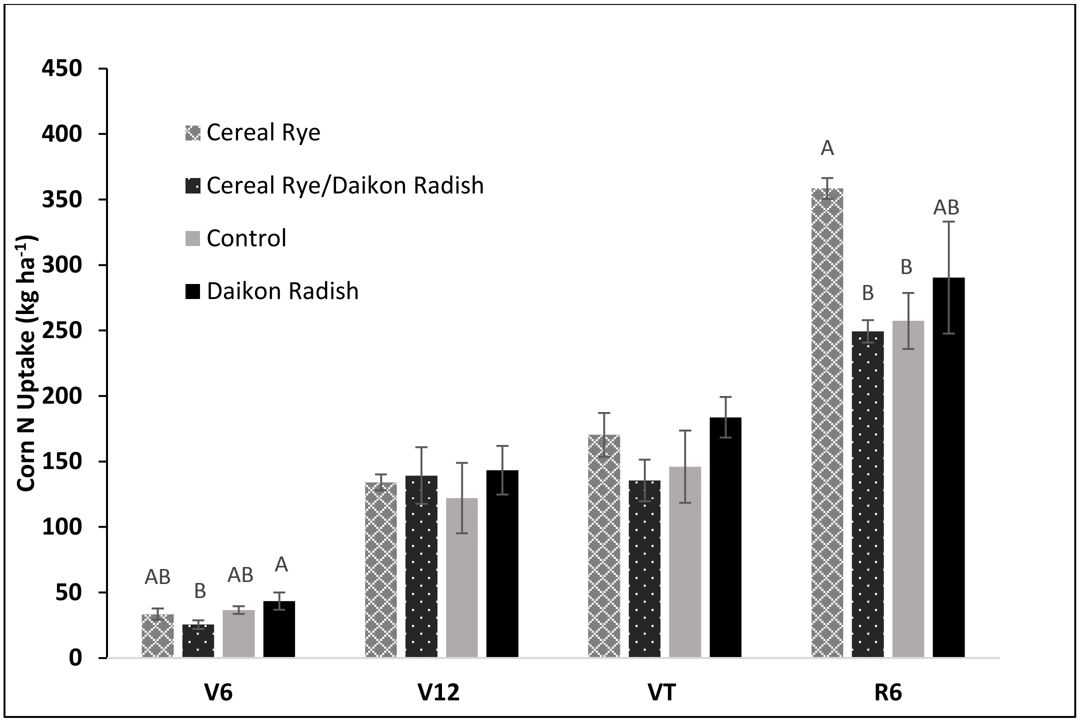

Figure B-5. Average crop N uptake (kg ha^{-1}) at 200 kg N ha^{-1} by growth stage (2014-2015). Samples collected throughout both corn growing seasons. Different letters indicate significant difference at individual growth stages (Alpha level of 0.05). No significant differences at V12 or VT.

Table B-11

Crop Uptake at 200 kg N ha^{-1} (V6) ANOVA (2014-2015)

Source of Variation	DF	F Value	Pr > F
treatment	3	4.58	0.0196
year	1	0.57	0.4636
block	2	1.14	0.3479
treatment*year	3	0.58	0.6386

Note: ANOVA table depicts the response variable (V6 crop uptake) and probability values for each source of variation.

Table B-12

Crop Uptake at 200 kg N ha^{-1} (V12) ANOVA (2014-2015)

Source of Variation	DF	F Value	Pr > F
treatment	3	0.38	0.7661
year	1	11.04	0.005
block	2	0.59	0.5674
treatment*year	3	1.64	0.2254

Note: ANOVA table depicts the response variable (V12 crop uptake) and probability values for each source of variation.

Table B-13

Crop Uptake at 200 kg N ha^{-1} (VT) ANOVA (2014-2015)

Source of Variation	DF	F Value	Pr > F
treatment	3	1.89	0.1779
year	1	19.83	0.0005
block	2	0.2	0.8172
treatment*year	3	0.25	0.8612

Note: ANOVA table depicts the response variable (VT crop uptake) and probability values for each source of variation.

Table B-14

Crop Uptake at 200 kg N ha^{-1} (R6) ANOVA (2014-2015)

Source of Variation	DF	F Value	Pr > F
treatment	3	8	0.0024
year	1	6.06	0.0275
block	2	1.02	0.3866
treatment*year	3	0.11	0.9532

Note: ANOVA table depicts the response variable (R6 crop uptake) and probability values for each source of variation.

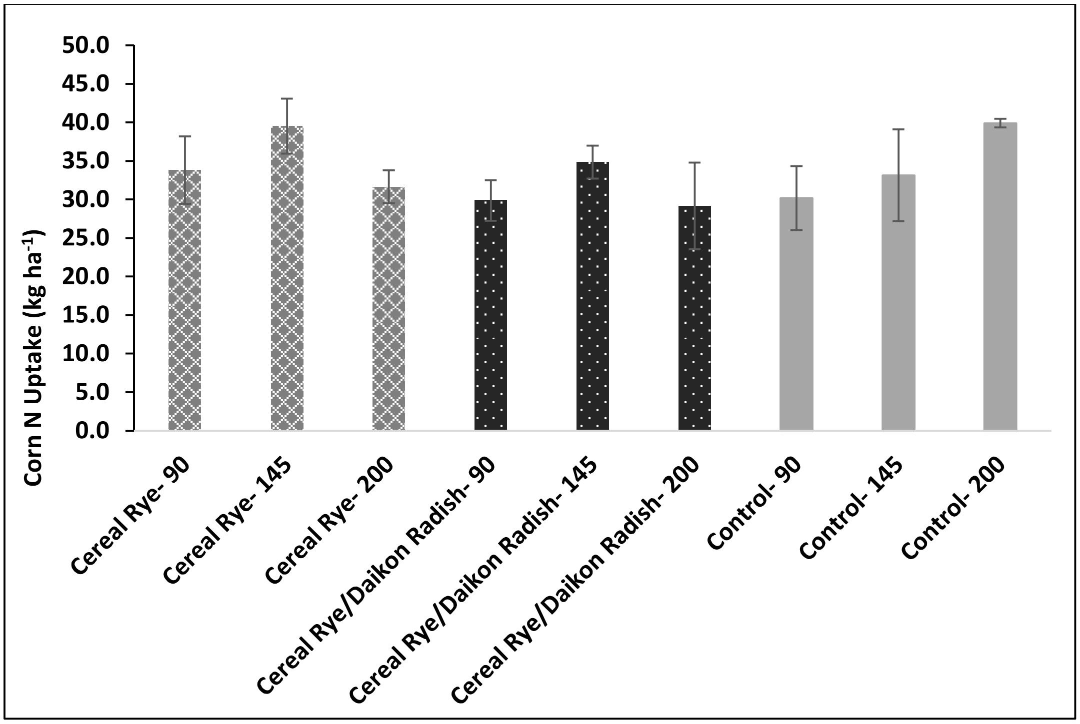

Figure B-6. Crop N uptake (kg ha^{-1}) by rate. Samples collected at V6 (2014).

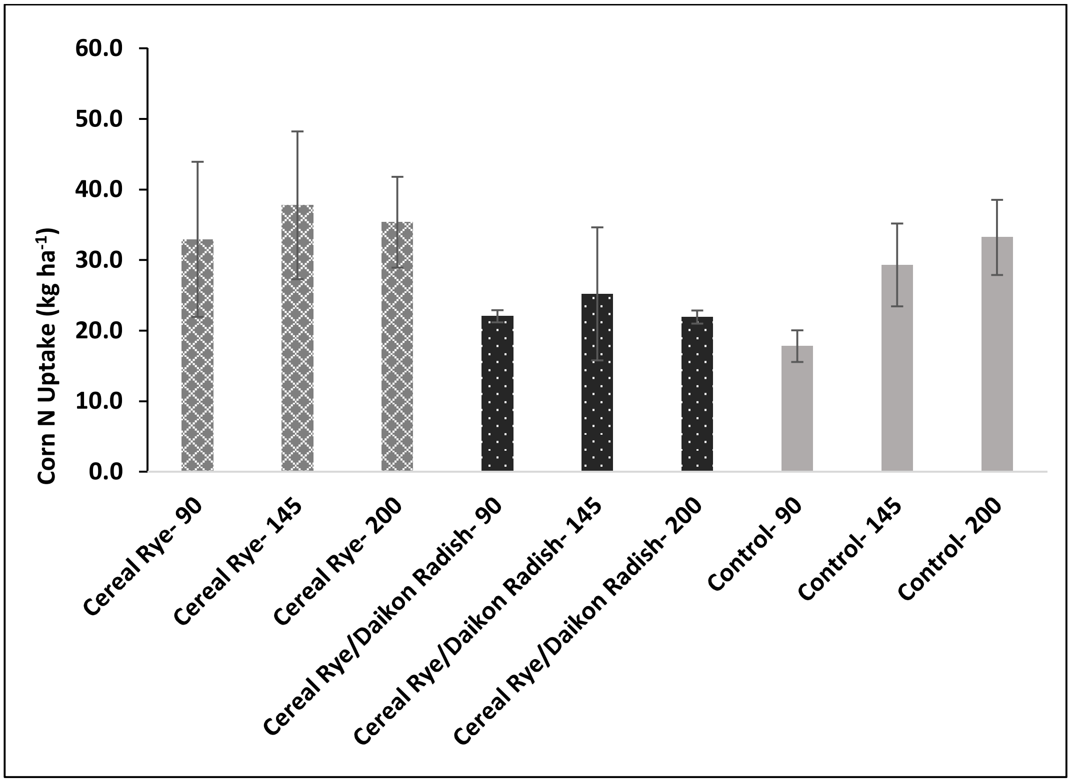

Figure B-7. Crop N uptake (kg ha^{-1}) by rate. Samples collected at V6 (2015).

Table B-15

Crop Uptake by Rate (V6) ANOVA (2014-2015)

Source of Variation	DF	F Value	Pr > F
treatment	2	3.24	0.0516
year	1	4.04	0.0525
rate	2	1.66	0.2061
block	2	1.9	0.1651
treatment*year	2	1.16	0.3268
treatment*rate	4	1.02	0.4126
year*rate	2	0.17	0.8474
treatment*year*rate	4	0.16	0.9565

Note: ANOVA table depicts the response variable (V6 crop uptake) and probability values for each source of variation.

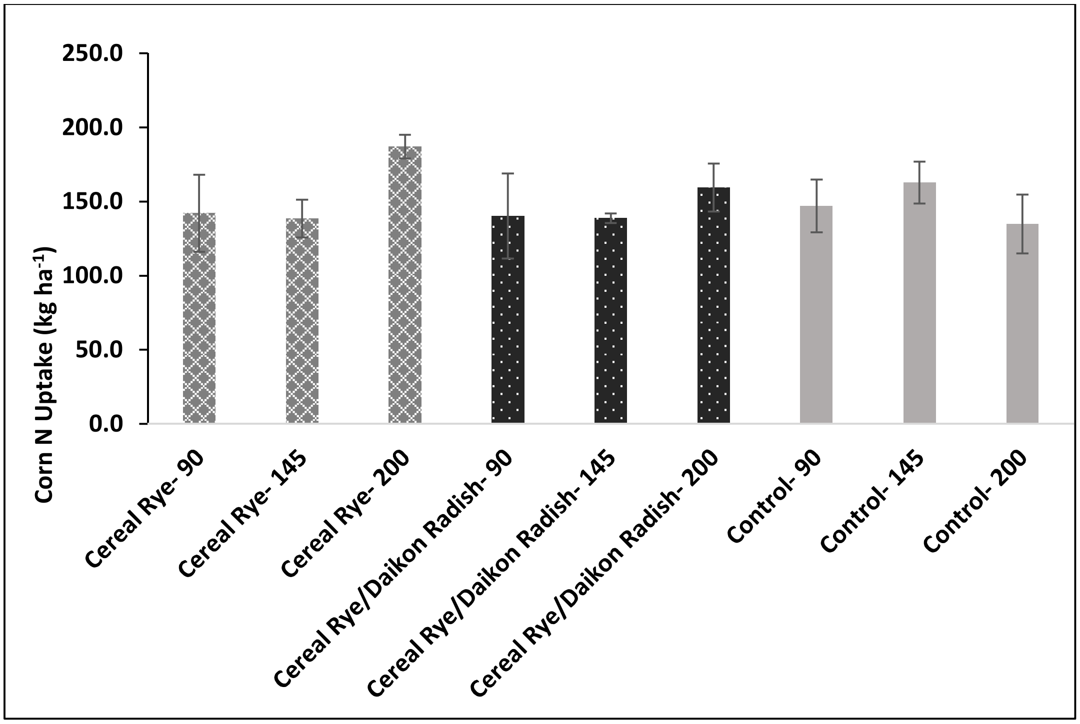

Figure B-8. Crop N uptake (kg ha^{-1}) by rate. Samples collected at V12 (2014).

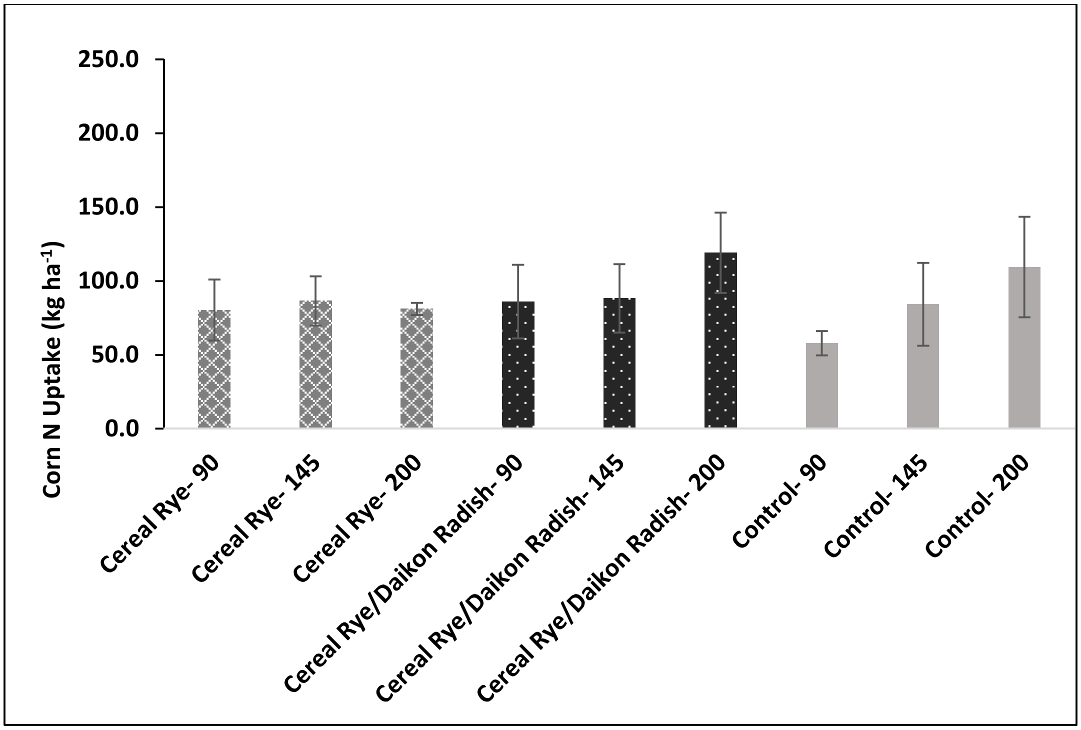

Figure B-9. Crop N uptake (kg ha^{-1}) by rate. Samples collected at V12 (2015).

Table B-16

Crop Uptake by Rate (V12) ANOVA (2014-2015)

Source of Variation	DF	F Value	Pr > F
treatment	2	0.13	0.8825
year	1	40.72	<.0001
rate	2	1.92	0.1619
block	2	0.74	0.4857
treatment*year	2	0.57	0.5726
treatment*rate	4	0.29	0.8849
year*rate	2	0.12	0.8906
treatment*year*rate	4	1.15	0.352

Note: ANOVA table depicts the response variable (V12 crop uptake) and probability values for each source of variation.

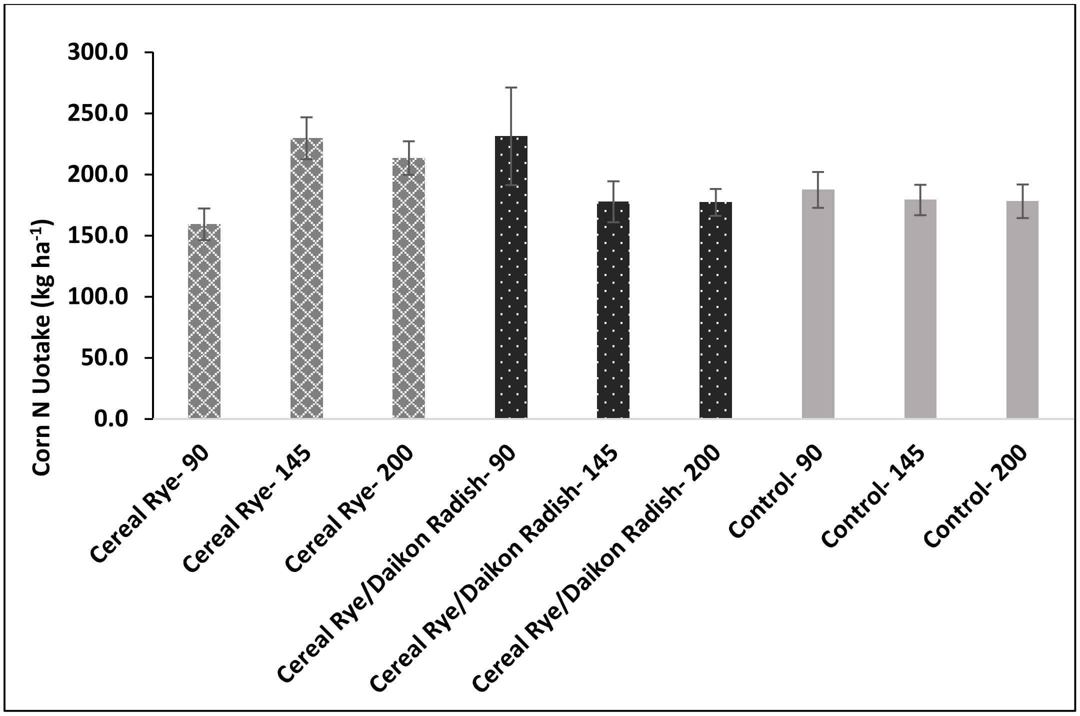

Figure B-10. Crop N uptake (kg ha^{-1}) by rate. Samples collected at VT (2014).

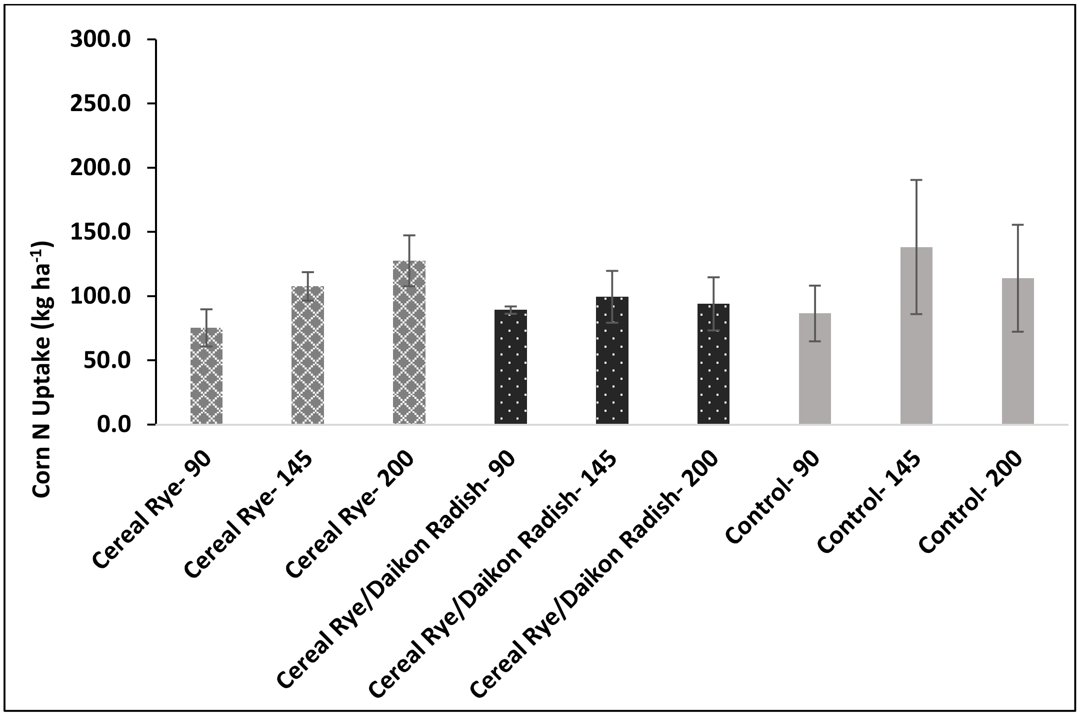

Figure B-11. Crop N uptake (kg ha^{-1}) by rate. Samples collected at VT (2015).

Table B-17

Crop Uptake by Rate (VT) ANOVA (2014-2015)

Source of Variation	DF	F Value	Pr > F
treatment	2	0.15	0.8644
year	1	63.73	<.0001
rate	2	0.85	0.4379
block	2	0.35	0.7045
treatment*year	2	0.84	0.4389
treatment*rate	4	1.74	0.164
year*rate	2	0.8	0.4574
treatment*year*rate	4	0.78	0.5488

Note: ANOVA table depicts the response variable (VT crop uptake) and probability values for each source of variation.

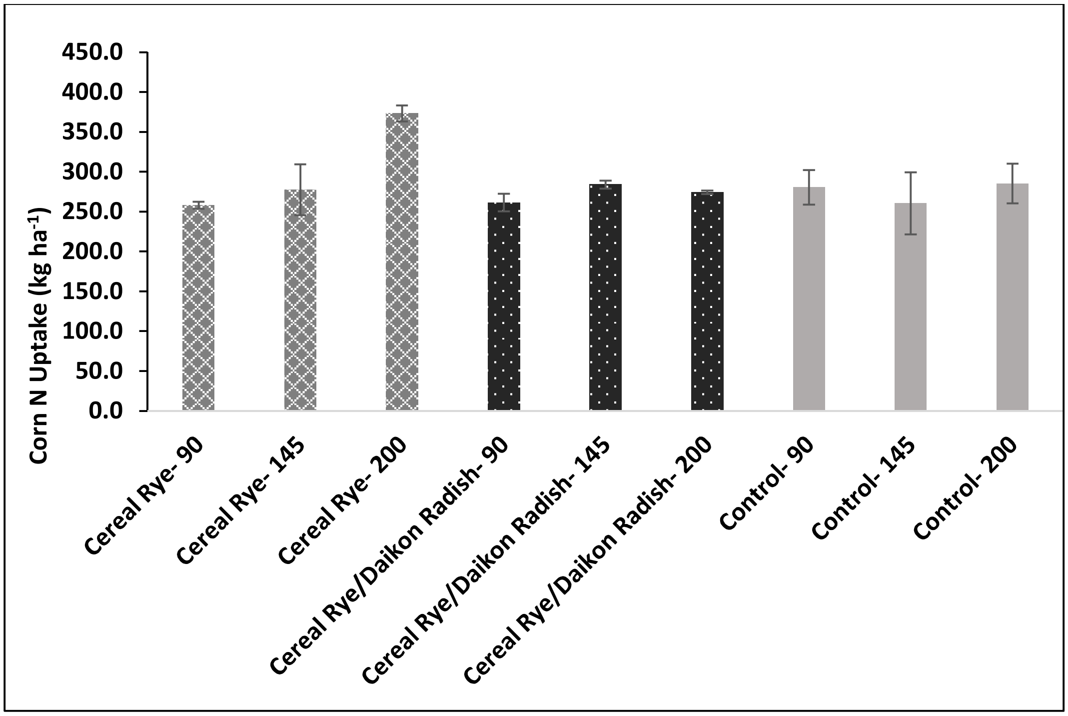

Figure B-12. Crop N uptake (kg ha^{-1}) by rate. Samples collected at R6 (2014).

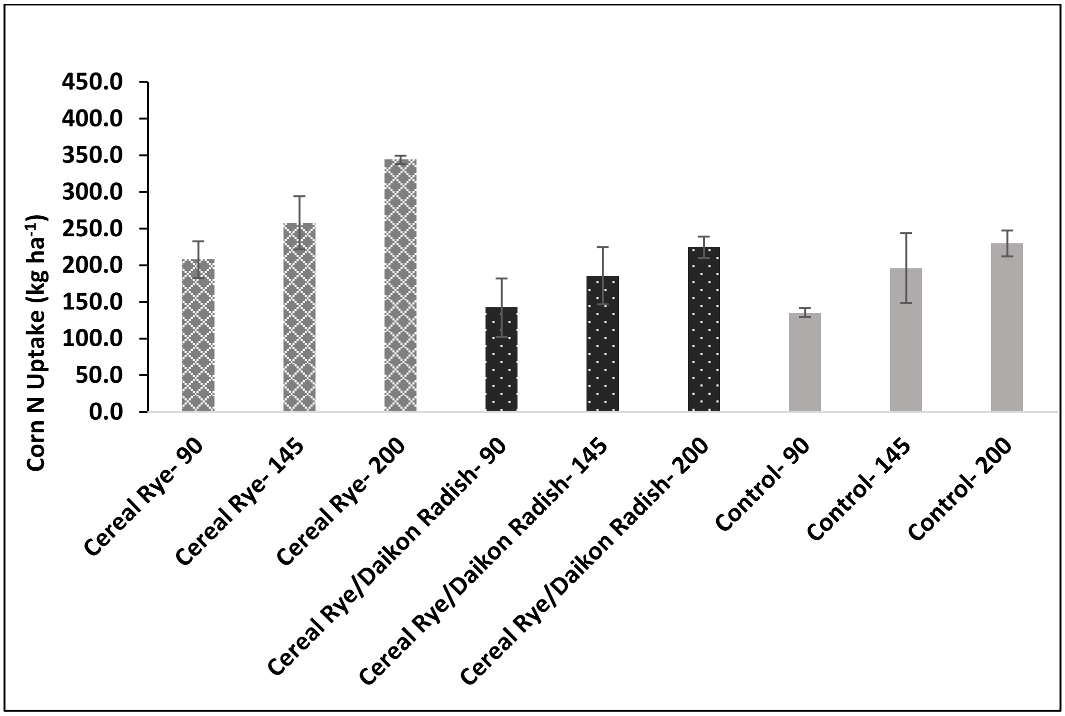

Figure B-13. Crop N uptake (kg ha^{-1}) by rate. Samples collected at R6 (2015).

Table B-18

Crop Uptake by Rate (R6) ANOVA (2014-2015)

Source of Variation	DF	F Value	Pr > F
treatment	2	9.57	0.0005
year	1	33.17	<.0001
rate	2	12.55	<.0001
block	2	0.71	0.4992
treatment*year	2	2.31	0.115
treatment*rate	4	1.83	0.1452
year*rate	2	2.17	0.1303
treatment*year*rate	4	0.4	0.8098

Note: ANOVA table depicts the response variable (R6 crop uptake) and probability values for each source of variation.

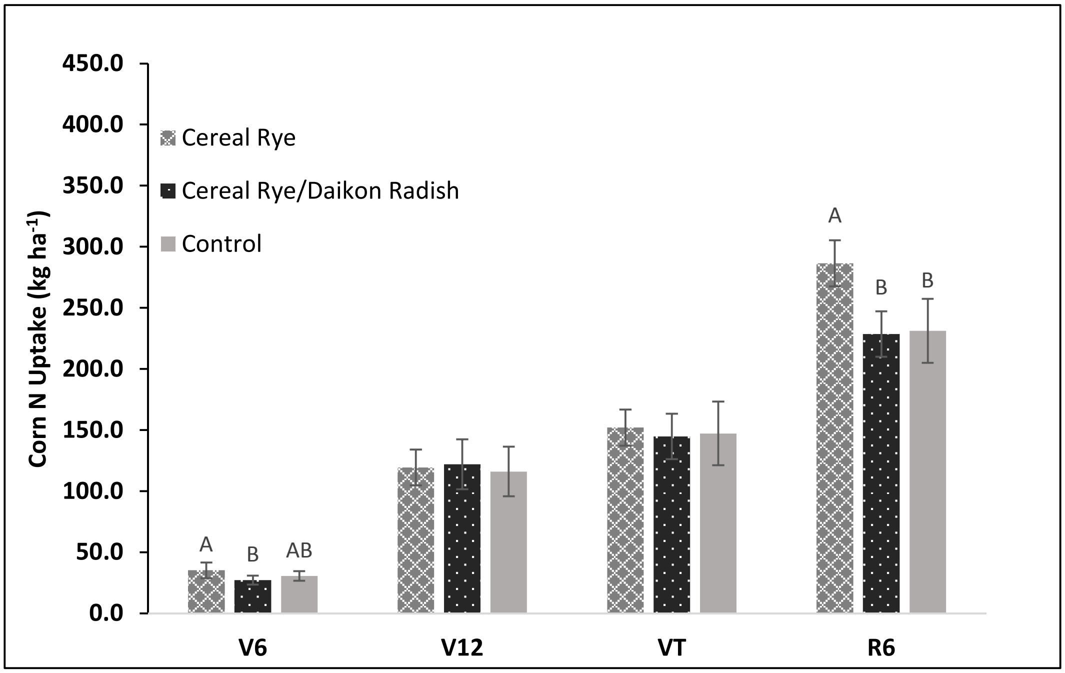

Figure B-14. Average crop N uptake (kg ha^{-1}) despite rate by growth stage (2014-2015). Samples collected throughout both corn growing seasons. Different letters indicate significant difference at individual growth stages (Alpha level of 0.05). No significant differences at V12 or VT.

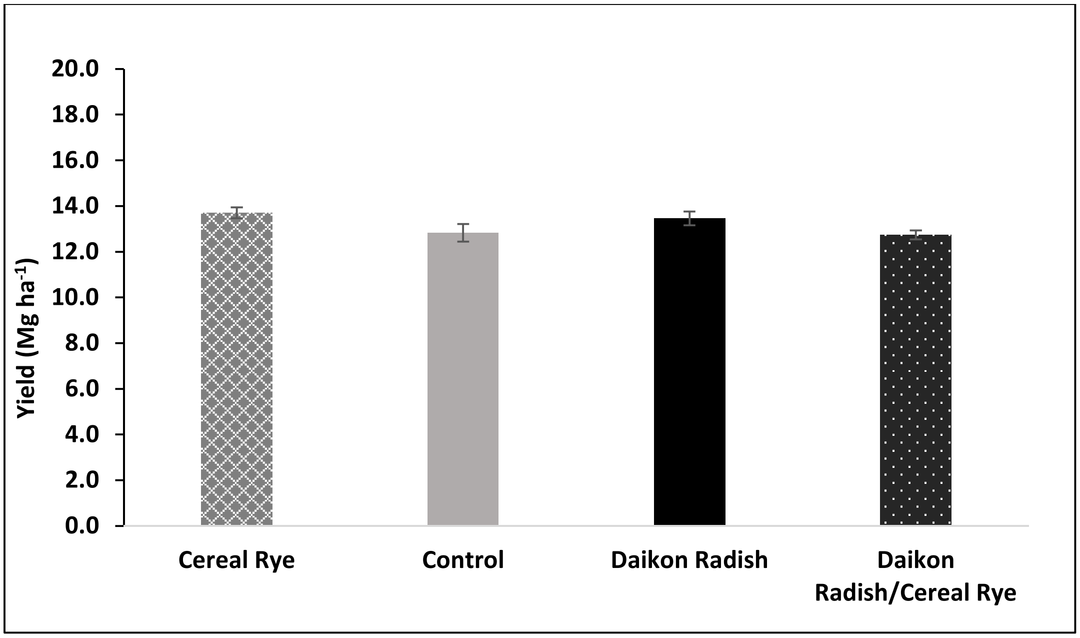

Figure B-15. Corn yield (Mg ha^{-1}) by treatment at 200 kg N ha^{-1}. Samples collected at harvest (2014).

Table B-19

2014 Grain Yield at 200 kg N ha^{-1} ANOVA

Source of Variation	DF	F Value	Pr > F
treatment	3	2.15	0.1946
block	2	0.23	0.804

Note: ANOVA table depicts the response variable (grain yield) and probability values for each source of variation.

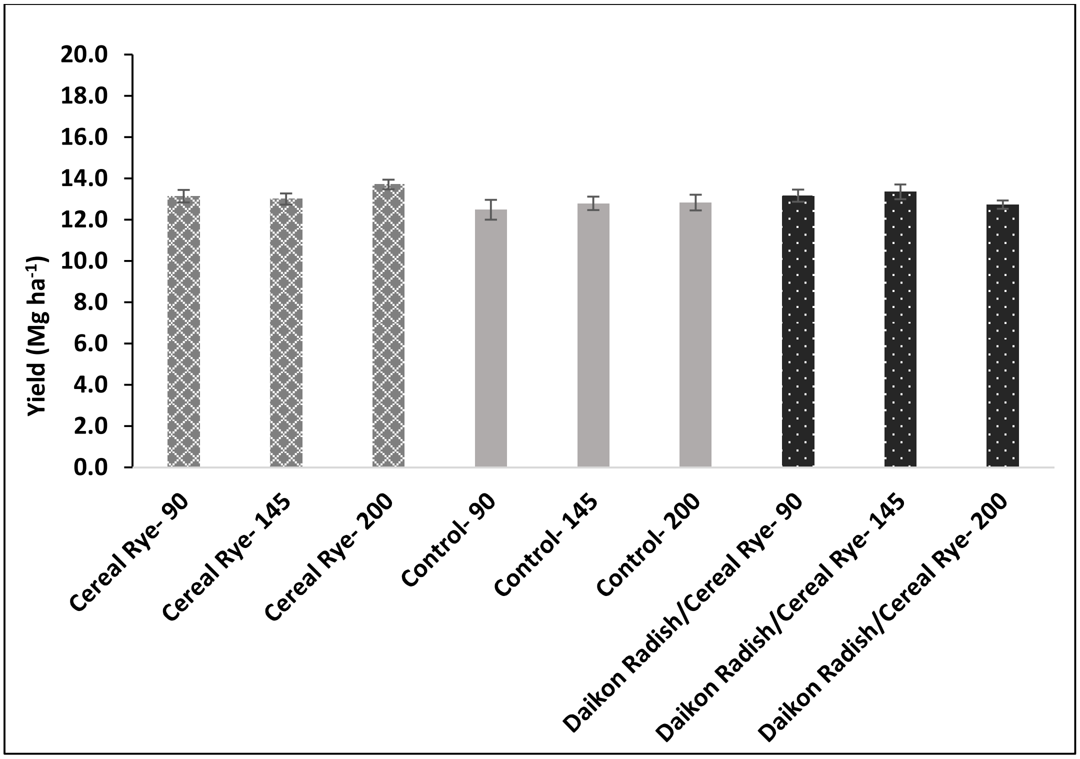

Figure B-16. Corn yield (Mg ha^{-1}) by treatment and rate. Samples collected at harvest (2014).

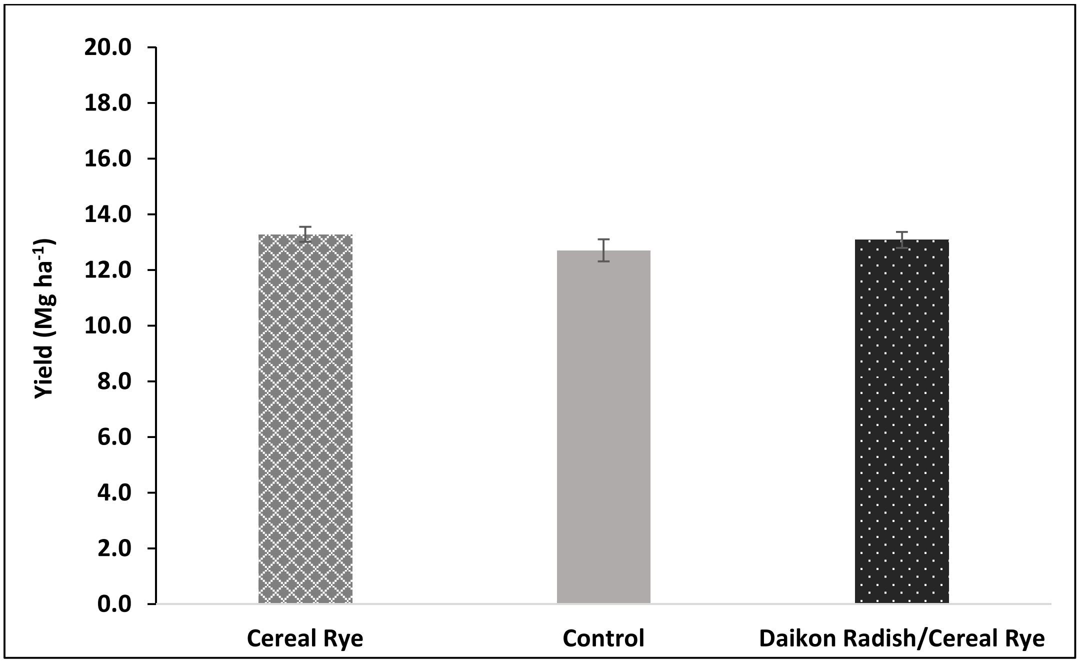

Figure B-17. Corn yield (Mg ha^{-1}) by treatment, despite application rate. Samples collected at harvest (2014).

Table B-20

2014 Grain Yield ANOVA

Source of Variation	DF	F Value	Pr > F
treatment	3	2.22	0.1142
rate	2	0.34	0.7128
block	2	2.34	0.1195
treatment*rate	6	0.94	0.4870

Note: ANOVA table depicts the response variable (grain yield) and probability values for each source of variation.

Table B-21

Corn Yield despite Rate of Application

Orthogonal Contrast (2014)	DF	F Value	Pr > F
Compare cereal rye with control	1	5.01	0.03
Compare cereal rye/daikon radish with control	1	2.16	0.15

Note. Displaying orthogonal contrast data directly comparing the yield between treatments, despite the rate of application (Alpha level of 0.05).

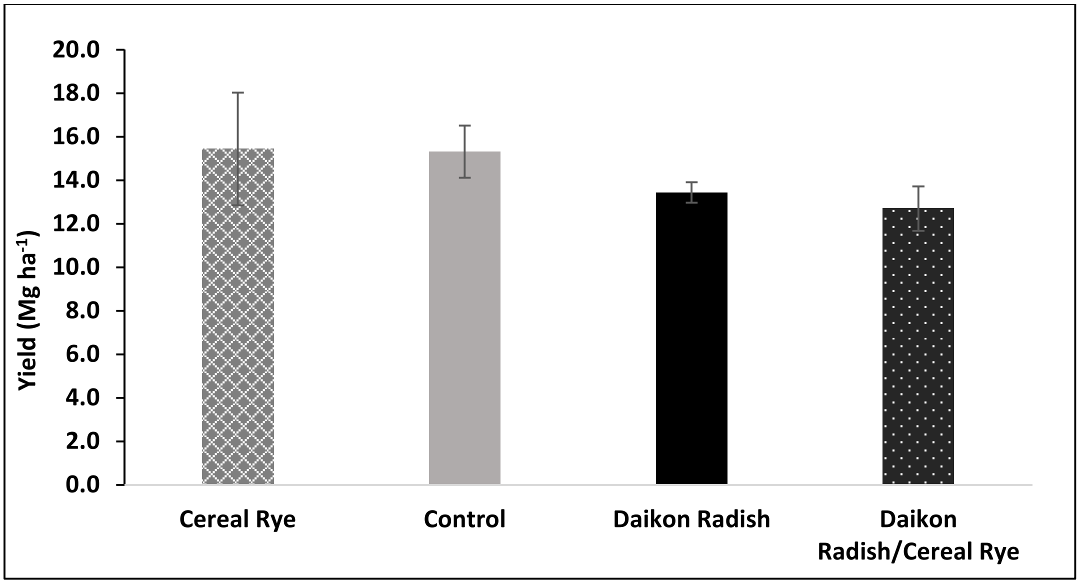

Figure B-18. Corn yield (Mg ha^{-1}) by treatment at 200 kg N ha^{-1}. Samples collected at harvest (2015).

Table B-22

2015 Grain Yield at 200 kg N ha^{-1} ANOVA

Source of Variation	DF	F Value	Pr > F
treatment	3	0.8	0.536
block	2	1.04	0.4084

Note: ANOVA table depicts the response variable (grain yield) and probability values for each source of variation.

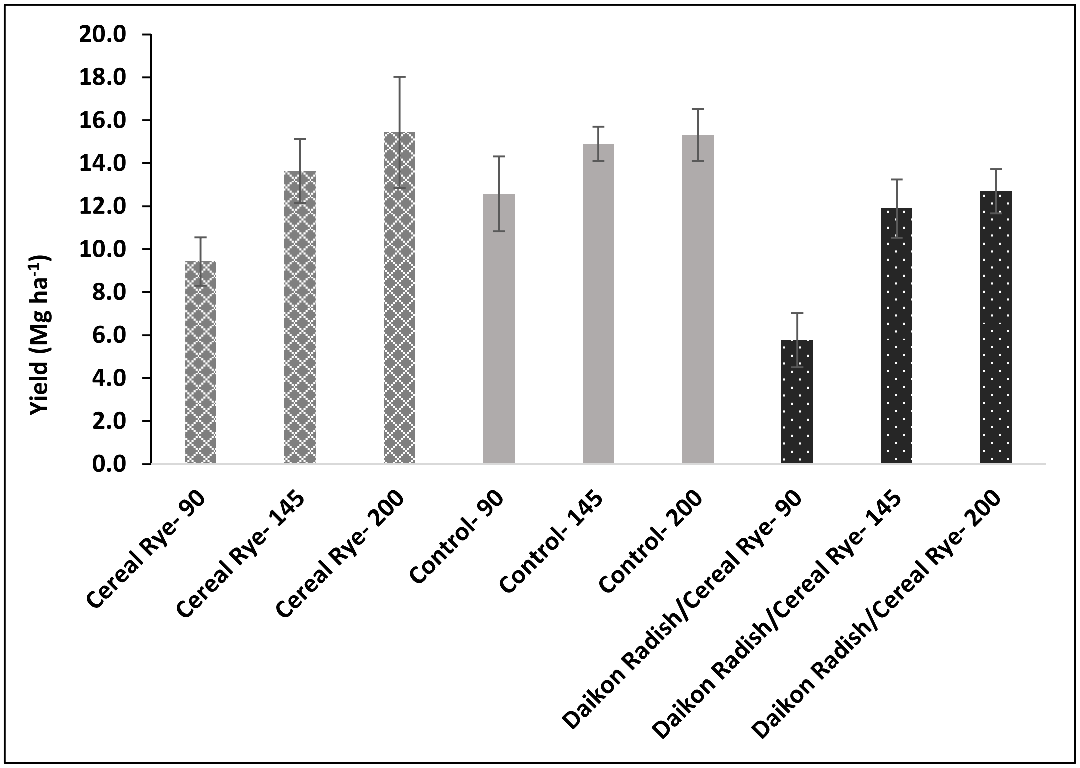

Figure B-19. Corn yield (Mg ha^{-1}) by treatment and rate. Samples collected at harvest (2015).

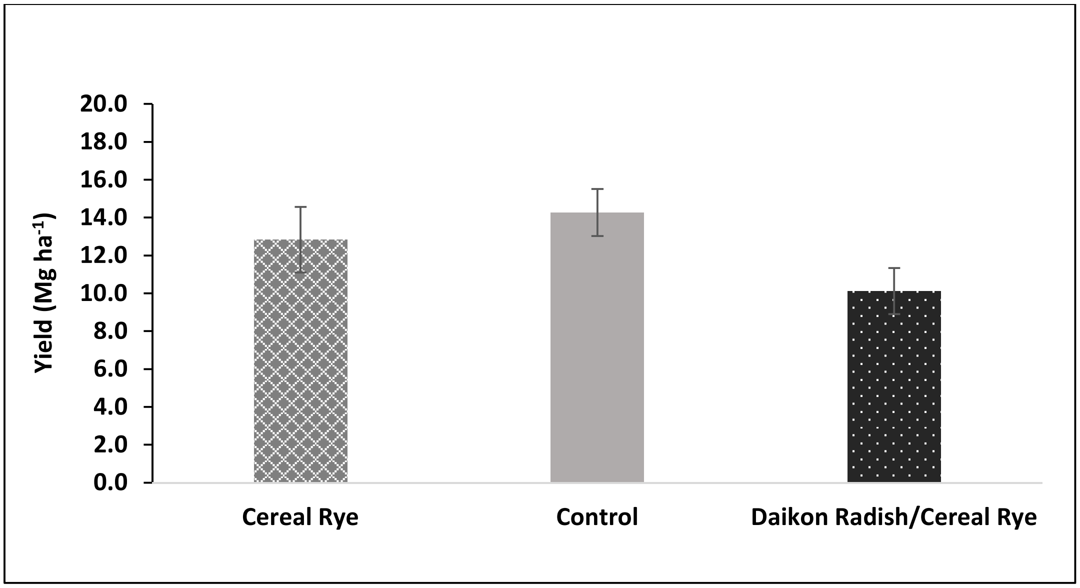

Figure B-20. Corn yield (Mg ha^{-1}) by treatment, despite application rate. Samples collected at harvest (2014).

Table B-23

2015 Grain Yield ANOVA

Source of Variation	DF	F Value	Pr > F
treatment	3	5.47	0.0058
rate	2	18.17	<.0001
block	2	1.30	0.2938
treatment*rate	6	0.60	0.7276

Note: ANOVA table depicts the response variable (grain yield) and probability values for each source of variation.

Table B-24

Corn Yield despite Rate of Application

Orthogonal Contrast (2015)	DF	F Value	Pr > F
Compare cereal rye with control	1	0.89	0.35
Compare cereal rye/daikon radish with control	1	7.50	0.01

Note. Displaying orthogonal contrast data directly comparing the yield between treatments, despite the rate of application (Alpha level of 0.05).