**Influence of cereal rye spring termination timing and herbicide type on soil nitrate and
litter composition**

by

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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

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ABSTRACT

Human activity has dramatically altered the natural nitrogen (N) cycle by tripling annual terrestrial N₂ fixation through legume cultivation and ammonia synthesis. The predominance of annual grain cropping systems leads to fallow fields between growing seasons. In the upper Midwest United States, fallow fields are prone to nitrate (NO₃) loss from soils to rivers and streams. This loss occurs mainly in the spring, as warm temperatures allow microbes to convert soil N to NO₃, and spring rains lead to NO₃ moving out of fields, largely through drainage. Cover crops are plants that are grown to improve or manage soil nutrients and structure instead of for harvest. In Iowa, the cold-tolerant cover crop cereal rye (*Secale cereale* L.) is well-suited to reduce NO₃ loss by using NO and water when annual grain crops, such as corn, soybeans, or other plants grown for grain, are not growing and using NO₃. However, the ability to grow cover crops is affected by the grain crop system in which they are grown. Rye must be terminated 10 days before corn (*Zea mays* L.) planting to maintain corn yield, but rye can be terminated any time before soybean (*Glycine max* L.) planting without affecting production. Since soybeans are planted on average 14 days later than corn, rye before soybeans can potentially have an average of 24 extra days to accumulate NO₃, especially important at a time when most NO₃ is lost. In addition to grain crop, the method of cover crop termination may also affect the ability to grow cover crops. Farmers can choose from a variety of herbicides and times at which to terminate cereal rye prior to corn or soybean planting, which may affect the potential for soil NO₃ retention and N mineralization from decomposing rye that has been terminated. In a corn and soybean system in central Iowa, we investigated how cover crop presence, herbicide type, and herbicide timing affect soil nitrate, cover crop nitrogen accumulation, and cover crop decomposition. Herbicides included in the study were glyphosate and paraquat, which have different modes of

action – inhibition of shikimate pathway and Photosystem I, respectively. Two rye termination times before soybean were tested to simulate two different farmer rye management decisions: 1) termination of rye in soybean fields 10 days before corn planting, or 2) termination of rye several days before soybean planting. An early termination date occurred at least 10 days before corn seeding as is recommended by Sustainable Agriculture Research and Education (Clark, 2007), and a late termination date occurred several days before soybean seeding. On average, the late termination date was 28 days after early termination. Soil nitrate-associated-nitrogen ($\text{NO}_3\text{-N}$) was sampled weekly throughout the growing season. Findings were that in 2014, rye cover crop aboveground biomass accumulated 28 and 32 kg N ha^{-1} with carbon:nitrogen (C:N) ratios of 11:1 and 17:1 (early and late termination, respectively). In 2015, rye cover crop aboveground biomass accumulated 28 and 89 kg N ha^{-1} , with C:N ratios of 17:1 and 31:1 (early and late termination, respectively). In the spring, for at least 2 weeks before termination and for one to three weeks following termination, presence of rye significantly reduced soil nitrate concentrations by an average of 31% ($p < 0.1$). Soil $\text{NO}_3\text{-N}$ and decomposing rye aboveground biomass responses to herbicide treatment was variable across years. A repeated measures analysis of variance indicates that, compared to no cover crop and early-terminated cover crop treatments, soil $\text{NO}_3\text{-N}$ concentrations in late-terminated cover crop plots, averaged 71% lower for the additional three to four weeks that rye was allowed to grow before termination ($p < 0.1$). Terminating rye as late as possible before soybean planting will maximize cover crop N retention when $\text{NO}_3\text{-N}$ loss is greatest in Iowa. Cereal rye cover crop before soybean has great potential to reduce agricultural impacts on water quality without impacting yield.

CHAPTER I. GENERAL INTRODUCTION

Introduction

Human activity has dramatically altered the nitrogen (N) cycle, the largest change due to land-applied agricultural N fertilizer in the last century; a 200% increase from natural biological nitrogen fixation and lightning fixation (Fowler et al., 2013). While the predominant corn and soybean cropping system in Iowa used 1.8 billion pounds of land-applied N to produce over 2.4 billion bushels of corn and nearly 500 million bushels of soybeans in 2014 (NASS QuickStats, 2012; 2014), Iowa fields are typically fallow when corn and soybeans are not growing (Wallander, 2013). Thus a typical corn-soybean system leaves little living land cover to prevent soil particles and nutrients from leaving the field for 8 months (Zhou et al, 2014).

In the spring, prior to vigorous corn or soybean growth, N from decomposing plant matter, soil organic matter (OM), and fertilizer, is converted to nitrate (NO_3), a soluble form of N. Nitrate is a major source of the essential element N for plant growth, but it is also easily lost to rivers and streams. Soil NO_3 loss occurs when water movement through the soil is high and plant uptake of NO_3 is low; in Iowa, this typically occurs in the spring and fall (Helmets et al., 2005).

Midwest rivers drain to the Gulf of Mexico, where nutrients from upstream farms accumulate. High nitrate concentrations in aquatic ecosystems can dramatically increase algal populations, called algal blooms (Rabalais et al., 2001, USEPA, 2013). When the algal blooms die, bacteria use oxygen to decompose algal cells, resulting in a hypoxic zone where low oxygen levels persist. This water is uninhabitable for aquatic wildlife, much of which need oxygen to live. Low oxygen levels are deadly for slow-moving sea creatures and displace fish populations,

impacting livelihoods of fisherpeople (USEPA, 2013). The hypoxic zone in the Gulf of Mexico is the second largest in the world, and is a direct result of nutrient loss from Midwest agricultural systems.

The consequences of NO_3 loss affect local communities as well as creating national environmental concerns. In Iowa, high NO_3 , reported as nitrate-associated nitrogen ($\text{NO}_3\text{-N}$) concentrations in rivers and streams, has led to several water quality issues. Nitrate-N concentrations in excess of 11 ppm can be fatal to infants and immunocompromised individuals, as it interferes with the blood's ability to transport oxygen (Bryan and van Grinsven, 2013). The U.S. Environmental Protection Agency (EPA) has set drinking water standard of less than 10 ppm $\text{NO}_3\text{-N}$ (EPA, 2004). Some public water systems rely on surface waters and groundwaters which can be vulnerable to nitrate contamination. This nitrate removal can be costly. In 2015, the Des Moines Water Works spent an average of \$10,000 each day the nitrate removal facility treated drinking water (Des Moines Water Works, 2015). Smaller communities, which do not have the resources to cover the cost of installment and use of nitrate removal facilities, must focus on preventing NO_3 loss from agricultural fields in the first place (Eller, 2015). Additionally, NO_3 accumulation in lakes and rivers can influence algal blooms (USEPA, 2013), which can be unpleasant and even dangerous for human recreation and wildlife due to algal toxins.

Nitrate loss is costly for farmers as fertilizer N makes up 8-11% of input costs per hectare of modern grain farming (Plastina, 2015). Agricultural fields with corn and soybean crops are the largest source of aquatic N pollution in the Gulf of Mexico, accounting for over 50% of aquatic N pollution from the Mississippi River Basin (Alexander et al., 2007), likely due to a long bare fallow period (Tonitto et al., 2006). It is unlikely that the corn-soybean system will shift in the

coming decades due to the complex infrastructure of transportation, research, government subsidies, knowledge bases, and specialized equipment that has evolved to support grain production. In lieu of dramatic land use changes, and with a need for resilient agriculture in light of climate change, agricultural research must emphasize improving in-field NO₃ retention in the dominant corn-soybean system.

To improve conditions in the Gulf of Mexico, the EPA called for the corn belt to reduce NO₃ loss by 45% (USEPA, 2013). Iowa responded by establishing the Iowa Nutrient Reduction Strategy (INRS) in 2013 (INRS, 2013) to summarize existing research on N management techniques in Iowa and predict the efficacy of combining management practices in Iowa. The INRS determined that a combination of on- and off-farm strategies must be implemented to achieve 42% reduction of agricultural field NO₃ loss to the Gulf of Mexico. One effective strategy is to use cover crops to grow between crop harvest and crop seeding.

Planting cover crops instead of leaving fields fallow over the winter is one way farmers can manage field N. Like natural systems that are typically dominated by perennial plants, cover crops can complement annual crop growth by increasing land cover and nutrient immobilization over the winter (Asbjornsen, 2014). For purposes of meeting EPA's NO₃ reduction target, this study explores one non-leguminous cover crop that grows well in Iowa, cereal rye (*Secale cereale* L.). Cereal rye is an overwintering cover crop that grows at low temperatures. Due to its ability to survive Iowa winters and use N in the spring as it regrows, it is effective at reducing NO₃ by 31% on average (INRS, 2013).

One major limitation to using cereal rye is timing both rye termination and grain crop planting during the wet spring. Before corn, cereal rye must be terminated at least 10 days in advance to not affect corn yield (USDA-NRCS, 2013). In contrast to corn yields, soybean yields

are not affected by a cereal rye cover crop as long as rye is fully terminated before soybean planting (Ruffo et al, 2004). Thus, considering the average Iowa soybean planting date is 14 days later than corn (NASS QuickStats, 2015), the window in which to terminate rye before soybeans is 24 days longer than before corn. During this extra period of growth, rye can produce additional biomass and retain a significant amount of soil $\text{NO}_3\text{-N}$ because of the exponential accumulation of growing degree days in the late spring.

Rye termination time can affect decomposition. As plants mature, they achieve a higher ratio of carbon:nitrogen (C:N), and more complex C structures form (Robertson and Groffman, 2015 p. 427; Poffenbarger et al., 2015). Both of these properties make it harder for microbes to convert organic N to NO_3 during the decomposition process of terminated rye. Slower N loss reduces potential N export and increases organic matter (OM), but at the cost of available NO_3 for subsequent crops (Fog, 2008). More research is needed on rye maturity and other factors which influence NO_3 immobilization and loss, such as termination time, herbicide, incorporation, precipitation, and N fertilizer type. This thesis aims to determine the effects of termination timing and herbicide treatment on the rate at which N from decomposing rye becomes both available to plants and susceptible to export from the field, to better understand how on-field N cycles are affected by cover crops.

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CHAPTER 2. SPRING TIMING AND METHOD OF CEREAL RYE COVER CROP TERMINATION AFFECT SOIL NITRATE

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Abstract

Soil nitrate-nitrogen (NO₃-N) lost from agricultural fields is costly to farmers and diminishes air and water quality. Soil NO₃-N loss usually occurs after precipitation when soils are flooded and soluble NO₃-N is carried along with the water out of the reach of roots to surface or groundwater; in Iowa corn and soybean crop systems, this typically occurs in the early spring and late fall. Cereal rye (*Secale cereale* L.), a cold-tolerant cover crop, can reduce NO₃-N loss in annual grain cropping systems by using NO₃-N and water in between the summer grain crop growing season. Rye is planted in the fall, ideally in September, and terminated prior to corn or soybean planting. Rye must be terminated 10 days before corn (*Zea mays* L.) planting to prevent

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corn yield loss, but rye can be terminated any time before soybean (*Glycine max* L.) planting without affecting yield. Since soybeans are planted on average 14 days later than corn in Iowa, rye grown before soybeans can grow an average of 24 days more than rye grown before corn. No-till farmers can choose the time at which to terminate cereal rye prior to corn or soybean planting, and a burndown or post-emergent herbicide with which to terminate cereal rye. These selections may affect $\text{NO}_3\text{-N}$ retention in the cover crop biomass and subsequent N release from the decomposing biomass, especially because spring accumulation of growing degree days can greatly increase cover crop $\text{NO}_3\text{-N}$ uptake. In corn and soybean crop systems in central Iowa, we investigated how cover crop presence, herbicide mode of action, and herbicide application timing affect soil $\text{NO}_3\text{-N}$, cover crop N accumulation, and cover crop decomposition. Herbicides included in the study were glyphosate and paraquat, which have different modes of action – inhibition of shikimate pathway and Photosynthesis I, respectively. Two rye termination times before soybean were tested to compare two farm management decisions. The first is to terminate all rye approximately 10 days before corn, regardless of the following crop, to avoid multiple herbicide applications for the farmer. The second decision is to have two termination dates: to terminate rye before corn 10 days before corn planting and terminate rye at least one day prior to soybean planting; this would maximize rye growth and $\text{NO}_3\text{-N}$ retention. Soil $\text{NO}_3\text{-N}$ was sampled weekly throughout the growing season. A litterbag study followed rye N decomposition over the growing season. In 2014, rye cover crop aboveground biomass accumulated 28 and 32 kg N ha^{-1} with carbon:nitrogen (C:N) ratios of 11:1 and 17:1 (early and late termination, respectively). In 2015, rye cover crop aboveground biomass accumulated 28 and 89 kg N ha^{-1} , with C:N ratios of 17:1 and 31:1 (early and late termination, respectively). Belowground biomass was variable and only sampled in 2014. Rye significantly reduced spring soil $\text{NO}_3\text{-N}$

concentrations by an average of 31% compared to plots without rye, for the two weeks before termination and up to three weeks following termination ($p < 0.1$). Rye also significantly reduced fall soil $\text{NO}_3\text{-N}$ compared to plots without rye by an average of 31% ($p < 0.1$). A repeated measures analysis of variance indicated that compared to the early-terminated and no cover crop treatments, soil $\text{NO}_3\text{-N}$ concentrations remained an average of 71% lower in the late-terminated cover crop plots around the time of termination ($p < 0.1$), while cover crop treatment did not affect soybean yield. Soil $\text{NO}_3\text{-N}$ and decomposing rye aboveground biomass responses to herbicide mode of action treatment were variable across years and trends were inconsistent compared to $\text{NO}_3\text{-N}$ trends. Terminating rye as late as possible before soybean planting can maximize cover crop N retention at times when $\text{NO}_3\text{-N}$ loss is greatest in Iowa. Cereal rye cover crop before soybean has great potential to increase soil $\text{NO}_3\text{-N}$ retention without impacting yield.

Introduction

Anthropogenic activities including legume cultivation and Haber-Bosch ammonia synthesis have tripled terrestrial inorganic (fixed) N inputs (Fowler et al., 2013). When soil N exceeds plant requirements, it is susceptible to loss by subsurface drainage (when water leaves the field and enters streams), which accounts for most N export to rivers and streams (Lawlor et al., 2008; David et al., 2010; McSwiney et al., 2010). In Iowa, N leaching from agricultural fields in Iowa accounts for 92% of N in waterways, which mainly occurs in the form of nitrate-N ($\text{NO}_3\text{-N}$) (Iowa Nutrient Reduction Strategy, 2013). High $\text{NO}_3\text{-N}$ concentrations in water are common in the spring because there are no growing crops to use soil water or $\text{NO}_3\text{-N}$ (Crandall et al., 2005; Helmers et al., 2008), impacting drinking water safety, recreational water use, and

environmental water quality as evidenced by the hypoxic dead zone in the Gulf of Mexico (David et al., 2010; Rabalais et al., 2001).

The primary reason for $\text{NO}_3\text{-N}$ loss from agricultural fields is that annual grain systems are typically fallow between fall harvest and spring planting. In warm and wet soils, microbes transform organic N in soil organic matter and plant residues, which is not susceptible to leaching loss, to soluble $\text{NO}_3\text{-N}$, which is highly susceptible to leaching loss. When precipitation is sufficient to induce subsurface drainage, $\text{NO}_3\text{-N}$ is leached from the soil to waterways. Warm soil and copious precipitation coupled with a lack of crop demand for N and water make April through June the period of greatest $\text{NO}_3\text{-N}$ export from fields in Iowa (Zhou et al., 2014). The Iowa Nutrient Reduction Strategy (INRS) has identified cereal rye cover crops as an effective practice to reduce $\text{NO}_3\text{-N}$ loss in an annual grain production system (31% reduction; INRS 2013) as they reduce soil nitrate by assimilating N in plant tissue and reduce drainage through evapotranspiration (Ruffo et al., 2004; Gardner and Drinkwater, 2009; Qi and Helmers, 2010).

Annual cover crops are typically planted in the fall before or after crop harvest so that they establish root systems and thus better suited for rapid spring growth. These annual crops overwinter and must be terminated in the spring before corn and soybean seeding. Cover crops can be terminated with tillage, or, in a no-till system, with herbicides or a roller-crimper. After termination, N sequestered by the cover crop is returned to the soil as cover crop biomass is decomposed. Cereal rye (*Secale cereale L.*) is well-suited to Iowa due its ability to overwinter and continue immobilizing N in the spring, when $\text{NO}_3\text{-N}$ leaching is high.

To prevent corn yield reduction, rye should be terminated at least 7 to 10 days before seeding corn (Duiker and Curran, 2005). However, in contrast to systems planted with corn, rye can be terminated as close as one day prior to soybean planting without reducing yield (Ruffo et

al., 2004). Moreover, the average Iowa soybean planting date is 14 days later than corn (NASS Quickstats, 2015). Thus, due to the extra 10 days rye must be terminated before planting corn and the later soybean planting date, rye can grow an additional 24 days longer than rye in fields to be planted with corn (NASS QuickStats, 2015). During this extra period of growth, rye can produce a significant amount of biomass and retain a significant amount of soil $\text{NO}_3\text{-N}$ because of the exponential accumulation of growing degree days in the late spring.

The rate of N decomposition from cereal rye may also be affected by herbicide modes of action. We tested two herbicide modes of action: glyphosate [N-phosphonomethyl-glycine], and paraquat [1,1'-dimethyl-4,4'-bipyridinium]. Glyphosate, a systemic herbicide which inhibits protein synthesis via the shikimate pathway, is translocated throughout the plant, killing rye slowly (Amrhein et al., 1980). Paraquat, a contact herbicide that affects the plant only at the points of contact, induces the production of reactive oxygen species inside plant cells by disrupting the electron transport chain, causing rapid damage to the cell membranes and cell lysis (Funderburk and Lawrence, 1964).

The goal of this study was to determine how mode of termination and timing of rye termination before seeding row crops affect soil $\text{NO}_3\text{-N}$ and decomposition of rye over the growing season. We employed two field experiments. In the first field experiment, we measured the effects of: i) two herbicide modes of action and a rye cover crop on soil $\text{NO}_3\text{-N}$ concentrations in a corn-soybean crop rotation (Table 1), ii) two timings of rye termination and a rye cover crop on soil $\text{NO}_3\text{-N}$ concentrations in the soybean phase of the rotation used typically in Iowa (Table 1). The second field experiment measured the effects of herbicide modes of action and termination timing on terminated rye decomposition in soybean fields under central Iowan conditions by decomposing rye in mesh bags (Table 2).

The termination dates were designed to simulate two management options that are affected by the difference in corn and soybean planting dates. To hedge risk, many farms that use an annual corn-soybean rotation grow both corn and soybeans on different fields in any given year. Thus, the early termination treatment simulated a decision to terminate all rye on the same date prior to corn planting, regardless of the following crop. A farmer's termination schedule might be affected by workday logistics or equipment rental. The late termination treatment simulated a decision to terminate rye in corn fields on a different date than rye in soybean fields. This decision might be made to enhance ecosystem benefits that result from greater rye biomass accumulation.

Rye that is allowed to grow longer may lose organic N at a slower rate because the carbon:nitrogen (C:N) ratio increases as a plant matures (Brady and Weil, 1999 p. 454). The rate of N mineralization from decomposing cereal rye depends on the C:N ratio as well as environmental factors. When the C:N ratio of a plant substrate exceeds 25:1, mineralization generally slows because microbes need to find additional N to metabolize C. Thus, given the same moisture content and temperature, the C:N ratio of decomposing plant biomass may be the most significant remaining factor affecting the rate of decomposition due to its effect on microbial metabolism (Ruffo and Bollero, 2003; Zhang et al., 2008). Farmers could use cover crop C:N data and information about decomposition rates to make decisions about how much nitrogen to apply and when to best time it.

While sufficient growth and N uptake by a fall-seeded rye is less of a problem in warmer parts of the United States, Iowa's cold climate means that few GDDs occur in the early spring before corn planting. Unless rye is planted in early fall and has enough GDDs to mature, rye growth is limited and does not assimilate as much N from the soil. A less mature plant has a

lower C:N ratio, thus immobilizing less N than a more mature plant (Green and Blackmer, 1994; Brady and Weil, 1999, p. 456). Early terminated rye therefore has greater potential to lose N from decomposing biomass by the time spring planted crops begin to accumulate significant amounts of $\text{NO}_3\text{-N}$. Increased $\text{NO}_3\text{-N}$ release without crop growth can lead to greater $\text{NO}_3\text{-N}$ loss. We hypothesized that a later rye termination date before soybean planting would have a two effects on soil N compared to an early termination date: i) a decrease in soil $\text{NO}_3\text{-N}$ through prolonged rye growth and ii) a slow return of N to the soil due to increasing the C:N ratio of the rye biomass residue. Minimizing time between rye termination and soybean planting may better synchronize N availability with N use, reducing potential N loss.

Unlike glyphosate, paraquat physically bursts cell membranes (Knoche et al., 1994, Amrhein et al., 1980). Thus we hypothesize paraquat-treated rye will increase the rate of N loss from decomposing rye by providing a physical pathway to export N from cells to soil. We also hypothesize grain yield will not be affected when managed according to recommended guidelines of termination and timing treatment.

Methods

Field site

The study was conducted at the Iowa State University Agricultural Engineering Farm in Central Iowa (42°02'N, 93°76'W). The site was established in the fall of 2013 on a 0.97 ha field. Clarion loam soil accounted for 0.76 ha (fine-loamy, mixed, superactive, mesic Typic Hapludoll), and Canisteo silty clay loam soil accounted for 0.21 ha (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquoll) (<http://websoilsurvey.nrcs.usda.gov/app/>). The site has a 2-6% slope from west to east. There is no record of tile-drainage on the site. Before

initiation of the experiment in the fall of 2013, the site had a two-year experiment with continuous corn managed in various soil tillage strategies. In 2011 and earlier, the site was managed with fall disk ripper tillage and spring cultivation in a corn and soybean rotation. Daily precipitation and maximum daily temperature in 2014 and 2015 (Figure 1) and growing degree days (GDDs, not shown; cumulative GDDs calculated by hand) were taken from the Iowa Environmental Mesonet (2015).

Soil samples were collected on September 18th, 2014 for standard fertility analysis (pH, P, K, and lime) (<http://crops.extension.iastate.edu/>). Twenty six samples to 15 cm were taken from each block, with 13 samples taken from within the crop row, and 13 samples outside of the crop row. For each block, samples were homogenized, sieved through 4 mm mesh, and air-dried for 4 days. Results of the fertility tests indicated that P and pH levels in all blocks were agronomically optimum, so no lime was applied (Table 3). Blocks 1 and 2 were within optimum K levels, and blocks 3 and 4 were at low K levels. K was not applied in 2014 or 2015.

Crop systems

In the fall of 2013, two crop systems were established including: 1) continuous corn (*Zea mays* L.) and 2) a corn-soybean (*Glycine max* L.) rotation. Both crop phases of the corn-soybean rotation were present every year (Table 1). However, because the study site was completely planted with corn in 2013 (prior to this study), the 2014 corn phase of the corn-soybean system had corn following corn. In other words, the experiment did not include corn following soybean in 2014. Thus, the corn-soybean system planted with corn in 2014 and continuous corn systems were identically managed and combined for analyses in 2014 only.

Corn was planted at 79,074 seeds per hectare in 2014 and 84,016 seeds per hectare in 2015. Soybeans were planted at a rate of 345,948 seeds per hectare in both years. Both systems were managed without tillage. Corn was fertilized with 32% N urea ammonium nitrate (UAN) in water at a rate of 224 kg N/ha with a coulter injection unit on July 7th, 2014. Corn was not fertilized at seeding in 2014. In 2015, corn was fertilized at seeding with a starter fertilizer of 9-18-9 at a rate of 50 L/ha. On June 5th, 2015, continuous corn was fertilized with 32% N UAN with a coulter injection unit at a rate of 224 kg N/ha, and corn-following-soybean was fertilized at a rate of 168 kg N/ha. Soybean plots were not fertilized.

Experimental design

Experimental plots including crop system, cover crop, and herbicide mode of action treatments were arranged as an unbalanced randomized complete block design (Figure 2). Four experimental blocks were established to account for within-site variation in topography and soil type. Eight 12.2 x 15.2 m plots were established within each block. Plots contained 16 corn or soybean crop rows with 76 cm row-spacing. In the continuous corn system, two plots were established within each block: one with rye, and one without. In corn-soybean systems planted with corn in 2014, one plot was established without rye, and two plots were established with rye. In corn-soybean systems planted with soybean in 2014, one plot was established without rye, and two plots were established with rye. The two rye plots in both crop phases of the corn-soybean system allowed for sufficient plots for early and late rye termination treatments when the following crop was soybean. When these two rye plots were in a corn year, the rye was terminated in both plots at the same early date which was also the same for all continuous corn plots with rye.

All plots were split into two 6.1 x 15.2 m subplots each containing eight crop rows. In plots with rye cover crop, one subplot was treated with glyphosate (190 L/ha RoundUp PowerMax) for cover crop termination and the other was treated with paraquat dichloride (1.5 L Gramoxone). In 2014, rye was not fully terminated with paraquat, so an additional round of herbicide was applied to both paraquat- and glyphosate-treated corn plots with 7 L/ha Lumax EZ (S-metolachlor+atrazine+mesotrione) and 2.2 kg/ha RoundUp PowerMax on May 29, 2014. A mix of 1.8 L/ha UltraBlazer (acifluorfen) and 1.8 kg/ha Round Up PowerMax with an ammonium sulfate additive at a rate of 12 g/L was applied to both paraquat- and glyphosate-treated soy plots on June 11, 2014. These applications also treated emergent weeds. In 2015, weeds were treated in all plots with 2.2 kg/ha Outlook (dimethenamid-p) and 2.2 kg/ha RoundUp PowerMax on May 1, 2015, and again with 2.2 kg/ha RoundUp PowerMax in all plots on June 16, 2015. In plots without rye, the subplots were not treated differently.

Plot treatments

Each crop system was managed with and without a cereal rye (*Secale cereale* L.) cover crop. Rye was planted in fall after crop maturity and terminated with herbicide in the spring before corn and soybeans were planted. The experiment began in the fall of 2013 when rye was drill-seeded at a rate of 70 kg seed/ha after corn grain harvest on October 25th. In the fall of 2014, rye was hand-broadcast on September 12 at a rate of 112 kg seed/ha. Hand-broadcasting was used to simulate mechanical broadcasting, which allows for seeding cover crops prior to grain harvest. Planting cover crops into standing crops early in the fall increases the period of cover crop growth and NO₃-N uptake.

In systems that were to be planted with corn, the rye cover crop was terminated at least 10 days before corn planting. In contrast to systems to be planted with corn, rye preceding soybean planting was terminated on one of two dates: 1) an early termination date at the same date used prior to corn or, 2) a late termination date that was at least one day prior to soybean planting. The different rye termination dates prior to soybean simulated two rye management options: 1) termination of all rye cover crops approximately 10 days before corn planting regardless of the following crop (corn or soybean), or 2) termination of rye in fields to be planted to corn approximately 10 days before corn planting and termination of rye in fields to be planted to soybean approximately 1-3 days before soybean planting. Crop systems without rye were not treated with herbicides during the period of cover crop growth. In the spring of 2014, the early termination date of rye was April 25th, 14 days before corn planting on May 9th, and 26 days before soybean planting on May 29th. The late termination date was May 23rd, 6 days before soybeans were planted (Table 1). In the following spring, early termination was April 16th 2015, 15 days before corn was planted on May 1st, and 33 days before soybeans were planted on May 19th. Late termination was on May 13th, 6 days before soybeans were planted.

Soil sampling and analysis

Soil was sampled approximately weekly from each treatment plot from April through October in 2014 and 2015. At each sampling date, six 2.4-cm diameter soil cores were sampled to 76 cm per subplot and composited. In 2014, one subplot from each plot without rye was randomly selected each week for sampling, and in 2015, one subplot from each plot without rye was randomly selected in April to be sampled for the year. Field samplers avoided taking soil from fertilizer bands, which were generally visible for two months after application. Samples

were stored for no longer than 7 days at 1.6 °C. Whole core samples were mixed and weighed before testing. Nitrate was extracted from subplot samples by shaking a subsample in a solution of 2M KCl (approximately 5:1 extract: dry soil ratio) for 60 minutes. After shaking, the extract solution was filtered through Whatman 1 filter paper and frozen until analysis. Soil NO₃-N was determined using colorimetric analysis with a VCl₃ Griess-Ilosvay reaction (Hood-Nowotny et al., 2010). Soil gravimetric water content from each sample was determined by drying a subsample at the time of extraction at 105°C. Nitrate-N concentrations and soil water content from the soil samples were used to calculate the concentration of NO₃-N in dry soil.

Bulk density was used to convert the concentration of NO₃-N in dry soil to a per-area basis. Bulk density for plots in a majority of Clarion soil was approximated from Al-Kaisi et al (2010) on a Clarion loam soil in no-till management from central Iowa. The dry bulk density from depths of 0-5, 5-10, 10-15 cm, was averaged to find the average bulk density from 0-15 cm, and that value was averaged with the value for 15-30 cm to approximate the average dry bulk density to 30 cm. A Canisteo clay loam in no-till, which made up the majority of the soil type in the rest of the plots, was reported to have the same bulk density as the Clarion loam by Benjamin and Cruse (1987) in central Iowa.

Rye biomass sampling

Aboveground rye biomass was clipped at the soil surface within a 25 x 25 cm quadrat in 2014 and 2015. To capture the spatial variability of rye growth, three sub-sample quadrats were clipped from each split-plot: one from the middle of the interrow, one between the center of the interrow and crop row, and one in the center of the crop row. Although rye was planted in the fall of 2013, rye was not sampled in the fall of 2013 because it did not germinate. In the

following spring of 2014, rye germinated. Rye in the early termination treatment was sampled once before rye termination on April 23rd, which was two days before termination. Rye in the late termination treatment was sampled twice before termination on May 5th and May 20th, which were 18 and three days before termination. In the fall of 2014, rye was sampled after germination on October 24th in all plots, 43 days after rye was planted. In the following spring of 2015, rye in early termination treatments was sampled on April 15th, one day before early termination and rye in late termination treatments was sampled twice, once on April 15th and again two days before late termination, on May 11th. Rye plots in continuous corn were not sampled in the fall of 2014 due to time constraints. Biomass was dried in a forced-air dryer at 60°C to a constant mass, and weighed for total dry biomass. In 2014, whole samples were ground to 0.5 mm with a Udy mill. If whole sample biomass was small (<2 g), they were ground in a ball mill to prevent sample loss. In 2015, late-terminated biomass was too large to fit directly into the Udy mill, so large samples (>30 g) were ground in a Wiley mill to 2 mm, then a subsample was ground to 0.5 mm with a Udy mill. Samples were analyzed for total C and N by dry combustion (LECO CHN-2000 analyzer, LECO Corp., St. Joseph, MI). Data will be presented as total C and total N.

Belowground rye biomass was sampled in only 2014. Three 3.2 x 20 cm subsample soil cores were collected from each split-plot: two beneath rye plants, and one from bare soil to capture spatial variability. Belowground biomass samples were washed with an elutriator (Wiles et al, 1996) to remove clay, and dried overnight at 60°C. Sand was removed from the washed samples by floating and decanting the dry biomass in deionized water, then biomass was dried for two days at room temperature. Silt, debris, and the biomass of other plants were removed by

hand sorting. Rye belowground biomass samples were composited after weighing and before being processed for total C and N with dry combustion elemental analysis.

Rye decomposition

On the first day after each rye termination date in 2014 and 2015, aboveground rye biomass was sampled from 18 quadrats, 25 x 25 cm, in each subplot, and fresh rye was weighed, composited, and split into 18 equal subsamples by subplot (Table 4). Three of those subsamples were immediately dried for initial dry weight and elemental analysis. The remaining 15 subsamples were placed in litterbags fashioned from 1.2 mm fiberglass mesh, closed with a heat sealer, returned to their respective plots, and fastened to the soil surface with wire flags. As samples were taken after termination, initial post-termination rye biomass occasionally differed from pre-termination rye biomass. At a range of days-after-termination, three litterbags were collected from each subplot for a total of five dates (Table 2). Samples were dried and processed for elemental analysis of total C and N as described above.

On the same days that litterbags were collected in 2014, decomposing belowground biomass was collected with a 3.2 x 20 cm soil probe. Three soil cores were taken from each split plot, with two cores taken from next to rye plants, and one sample taken away from rye plants to capture the distribution of biomass. Belowground biomass samples were processed for biomass and elemental analysis of total C and N as described above. Decomposing belowground biomass was not sampled in 2015 due to time constraints.

Grain Yield

Corn and soybean grain yield was determined by harvesting the center four rows of each plot with a plot combine. Yields were adjusted to a dry weight.

Statistical Analysis

Analyses of soil NO₃-N, grain yields, and termination treatments were performed independently by year as repeated samples were paired within-year but not between years as crop phase and thus cover crop treatment changed within a plot from year to year. That is, plots in soybean in 2014 with two rye termination timings were in corn in 2015 with one rye termination timing. Block and plot were considered random, and plot was nested within block. Significant interactions ($p < 0.05$) within dates were subsequently analyzed across treatments. For all analyses, post-hoc comparisons of significant treatment effects were compared with Tukey's range test, and plot was nested within block. All data were log transformed to stabilize variance between early and late termination dates.

Soil NO₃-N in corn plots (continuous corn or corn-soybean systems) was analyzed using a repeated measures analysis of variance (RM ANOVA) with PROC MIXED for the effects of date and herbicide (SAS Institute, Cary, NC). Soil NO₃-N in soybean plots (corn-soybean systems) was analyzed using a repeated measures analysis of variance (RM ANOVA) using PROC MIXED for the effects of date, herbicide, and timing of rye termination. Aboveground and belowground decomposition of rye in soybean plots (corn-soybean system) were analyzed by date with a RM ANOVA using PROC GLIMMIX for the effects of date, herbicide, and timing of rye termination (SAS Institute, Cary, NC). Corn and soybean grain yields and rye aboveground and belowground biomass were analyzed by date with an RM ANOVA using

PROC MIXED for the effects of date, herbicide, and timing of rye termination (SAS Institute, Cary, NC).

For modeling litterbag decomposition, the percent of biomass TC and TN in the litterbags over time was fit with three models following Weider and Lang (1982), using R (RStudio Team 2016). The single-exponential model fit was $X = e^{-kt}$, where X is the percent TC or TN remaining at t days after termination, and k is the decomposition constant. The double-exponential model fit was $X = Be^{-k_1t} + (1-B)e^{-(k_1+k_2)t}$, where X is the percent TC or TN remaining at t days after termination, B is the percent of initial TC or TN that decomposes under the decomposition rate k_1 , while $(1-B)$ decomposes under the decomposition rate (k_1+k_2) . The asymptotic model (ASM) fit was $X = A + (1-A)e^{-kt}$ where X is the percent TC or TN remaining at t days after termination, A is the asymptote (the percent of the initial TC or TN which does not decompose), and k is the rate of decomposition at which $(1-A)$ decomposes. The models were compared for best fit using Akaike's Information Criterion (AIC) and Bayesian Information Criterion (BIC). The asymptotic model was the best fit for both years and %TC and %TN remaining. Full and reduced-factor asymptotic models were compared with two-way analysis of variance (ANOVA) to test the significance of herbicide type and timing of termination. Variables were only compared within years. Once insignificant terms were removed from the model, the decomposition rate k was calculated for each replicate, and Welch's t-test was performed to compare treatments.

Results

Rye Cover Crop Carbon and Nitrogen

Prior to termination in spring 2014, rye aboveground total carbon (TC) did not differ between treatments. However, at the respective termination times, late-terminated aboveground

TC and C:N ratio were both higher than at early-termination (Termination times: May 23rd vs. April 25th; Table 2). Rye total nitrogen (TN) was not significantly different between termination times. In 2015, late-terminated rye again produced more aboveground TC with a higher C:N ratio than early-terminated rye (Table 5). However, in contrast to 2014, TN in late-terminated rye was >200% more than early terminated rye (34 vs 87 kg N ha⁻¹).

Prior to termination in 2014, late-terminated rye produced 3.07 kg/ha in belowground TC, over twenty-five times higher than at early-termination (0.11 kg/ha, Table 6). Belowground TN in rye at late-termination was likewise five times higher (0.02 kg/ha and 0.11 kg/ha, respectively). The C:N ratio was not significantly higher at late-termination than at early-termination (27 and 20, respectively). Belowground biomass was not sampled in 2015.

Cover Crop Effects on Soil NO₃-N

Before termination in 2014, soil NO₃-N was not significantly different in no-rye treatments compared to rye treatments (Table 7 and 8, Figures 3 and 4). In 2015, however, soil NO₃-N was generally lower in rye treatments than no-rye treatments from November through mid-May (Tables 7-11, Figures 3-5). In late October of 2014, after rye was seeded, soil NO₃-N was significantly lower in plots with rye than in plots without rye (Tables 7-9, Figures 3 and 4). This trend persisted in the following November of 2015, however only in the plots following soybean (Table 11, Figure 4).

Herbicide and Cover Crop Effects on Soil NO₃-N

Soil NO₃-N was significantly affected by herbicide and presence of rye in continuous corn in 2014 (Table 7, Figure 3). In 2014, the soil NO₃-N response to herbicide varied by date,

with differences in soil $\text{NO}_3\text{-N}$ appearing after termination and remaining intermittently for two months. On average over the season, the no-rye treatment and glyphosate treatment had significantly lower soil $\text{NO}_3\text{-N}$ than the paraquat treatment. In fall 2014, after rye establishment, soil $\text{NO}_3\text{-N}$ in rye treatments was lower than in treatments without rye. In 2015, presence of rye in continuous corn significantly reduced soil $\text{NO}_3\text{-N}$ from April through May, but no differences were seen between paraquat and glyphosate treatments (Table 9).

Soil $\text{NO}_3\text{-N}$ in the corn phase of the corn-soybean system in 2015 was generally lower in the presence of rye from March through mid-June, but there was no main effect of herbicide (Table 10, Figure 3). In the soybean phase of the corn-soybean system, herbicide treatment did not affect soil $\text{NO}_3\text{-N}$ under a rye treatment (Tables 8 and 10).

Termination Timing and Cover Crop Effects on Soil $\text{NO}_3\text{-N}$

The soil $\text{NO}_3\text{-N}$ response to termination timing varied by date prior to the soybean phase of the corn-soybean system (Figure 4). In 2014, there was no main effect of termination timing. However, there was a significant date by termination timing interaction; for three weeks following early termination in 2014, early-terminated rye had higher soil $\text{NO}_3\text{-N}$ than late-terminated rye (Table 8). In 2015, early-terminated rye had higher soil $\text{NO}_3\text{-N}$ than late-terminated rye for six weeks following early termination (Table 11). The effect was significant within the year.

Rye Decomposition

In 2014 and 2015, early-terminated rye from litterbags had lower aboveground TC, TN, and C:N ratio over the time period sampled than late-terminated rye (Table 12, Figures 6-8).

Herbicide did not affect aboveground TC or TN, but did affect the C:N ratio in 2014. That year, glyphosate-treated rye had a significantly higher aboveground C:N ratio than paraquat-treated rye. However, there was no effect of herbicide on C:N ratio in 2015.

Rye belowground biomass sampled from soil cores from April through August in 2014 was highly variable and did not follow a trend over the course of the year (Table 6). Total belowground C and TN were not affected by termination timing or herbicide in 2014 (Table 13). Samples were not taken in 2015.

Herbicide Type and Termination Time Effects on Rye Decomposition Rate

The asymptotic model was a better fit than the single-exponential model and double-exponential model for both TC and TN. Comparing full and reduced models determined that herbicide type was not a significant factor contributing to the model, for both TC and TN. Timing of termination was a significant factor for TC ($p < 0.01$), and was near enough to the chosen significance factor ($\alpha = 0.05$) for TN ($p < 0.06$) to further compare how early and late termination times affected the decomposition rate k within year for both TC and TN. Though termination time did explain a significant amount of data in the model, k rates varied within each termination time and year, and ultimately the k was not significantly different between early and late termination times for either TC or TN in either year (Table 14).

Grain yields

Corn yield in 2014 was not significantly affected by presence of rye or herbicide type (Table 15). Soybean yields in 2014 were not affected by presence of rye, herbicide type, or timing of termination.

Discussion

Termination Timing Effects on Soil NO₃-N and Rye N Decomposition

Compared to all other treatments, the lower soil NO₃-N in late-terminated plots can lead to a lower NO₃-N leaching potential, because while drainage may not change as a result of soil cover, reduced NO₃-N due to plant immobilization ultimately leads to less NO₃-N loss (Qi et al., 2011; Kaspar et al., 2012).

Compared to early-terminated rye, late-terminated rye before soybean not only decreased soil NO₃-N after the date of early termination, but also led to reduced NO₃-N levels for one and three weeks after termination (2014 and 2015, respectively; Tables 8 and 10, Figure 4). Compared to the no-rye treatment, the reduction of soil NO₃-N concentrations in early- and late-terminated rye before soybean persisted for three and four weeks after respective termination dates in 2014 and 2015. This extended period of low NO₃-N levels after termination is likely a result of microbial communities immobilizing NO₃-N to decompose carbon-rich rye residues (Clark, 1997; Mirsky et al., 2011).

In the litterbag experiment, late-terminated rye had higher C:N ratios than early terminated treatments, which could make the rye more difficult for microbes to mineralize, therefore delaying rye decomposition and N mineralization (Table 12, Figure 8). Though termination time affected C:N ratios, all rye at respective termination times, except for late-terminated rye in 2015, had a C:N ratio of less than 24:1. A C:N ratio of 24:1 is optimal for microbial decomposition, as it allows microbes enough organic N to decompose a C source without immobilizing soil NO₃-N (Allison and Klein, 1962, Waggoner et al., 1998; Manzoni et al.,

2008). At late termination in 2015, rye reached the head emergence and had a C:N ratio of 31:1, and corresponded to the longest period of reduced soil $\text{NO}_3\text{-N}$ after termination (reduced soil $\text{NO}_3\text{-N}$ for three weeks; Tables 4 and 10).

In the litterbag experiment, late-terminated rye TN decomposition did not approach zero to as great an extent as early-terminated rye. For all treatments after 100 days, an average of 82% of rye TN had decomposed in both early- and late-terminated rye litterbags (Figure 7). However, in 2014 and 2015 respectively, 74 and 9.0 times the TN remained in the late-terminated rye litterbag compared to the early litterbag (2014: 0.08 and 5.6 kg TN ha^{-1} , 2015: 3.9 and 35 kg TN ha^{-1} , respectively; Figure 7). The proportion of remaining TN is similar to the values reported by Ranells and Waggoner (30%; 1996) and Helmers et al. (2005). The higher C:N ratio at late termination is likely the reason for less TN decomposition by the end of the sampling period (Manzoni et al., 2008; Ruffo and Bollero, 2003; Figure 8).

Herbicide Effects on Soil $\text{NO}_3\text{-N}$

The effect of herbicide type on $\text{NO}_3\text{-N}$ in all cropping systems varied between years and crop systems (Tables 6-11). In 2014, soil $\text{NO}_3\text{-N}$ was highest under paraquat-treated rye in continuous corn intermittently after termination (Table 7; Figure 3). In 2015 in continuous corn and in the corn phase of the corn-soybean system, soil $\text{NO}_3\text{-N}$ was again higher under paraquat-treated rye, however only on the first sample date after termination (Tables 9 and 11; Figures 3 and 5).

Paraquat did not increase soil $\text{NO}_3\text{-N}$ in fields to be planted with soybeans (Tables 8 and 10; Figure 3). An interaction between date and herbicide did affect $\text{NO}_3\text{-N}$ in the soybean phase,

but this indicated an effect of the presence of rye, not differences between herbicide types (Table 8; Figure 4).

Results of the litterbag study were inconsistent with both the lack of herbicidal effect on $\text{NO}_3\text{-N}$ before soybean, and paraquat increasing $\text{NO}_3\text{-N}$ in corn. Litterbags with paraquat-treated rye had a lower C:N ratio than litterbags with glyphosate-treated rye in 2014 (Table 12; Figures 7-8). Total C, TN, and C:N ratio of rye in litterbags were not affected by the paraquat treatment before soybean in 2015. As we did not see consistent trends between crops or years, we neither reject nor accept the hypothesis that paraquat increases the rate of TN decomposition; more experimental years are necessary.

For the first 10 days after late termination in 2015, TC and TN were lost at a faster rate than in previous work (Ranells and Waggoner, 1996; Ruffo and Bollero, 2003; Lawlor et al., 2008; Figures 6 and 7). This is due to a sharp decline in biomass sampled at the first and second date, which may be a result of sampling error.

Total C and TN were taken for belowground biomass samples, but variability in samples was great in 2014, probably due to spatial variability, so samples were not taken in 2015 (Table 5). Roots sampled with a wider core or with more replicates would be of interest in future herbicide studies, as the herbicide modes of action differed in their ability to translocate to roots.

Rye Growth

As expected, aboveground TC and TN at late-termination was higher than at early-termination in 2015 (Table 5, Figures 6 and 7). This is due to warm spring temperatures, which led to considerable increases in growing degree days for the late termination in both years (2014: 210 GDD, 2015: 257 GDD; Iowa Environmental Mesonet, 2015; Figure 1). This trend was

present in 2014, though differences were not consistently significant. This may be attributed to the lack of rye germination and growth in the fall of 2013 and poor rye establishment in the spring of 2014. Total C values observed at termination times were typical of rye TC in Iowa (180-1800 kg TC ha⁻¹, assuming 45% C; Johnson et al., 1998; Sawyer et al., 2013) except for samples taken at late-termination in 2015, when rye was terminated at a mature growth stage of partial heading (2700 kg TC ha⁻¹; Table 5, Figure 6). Rye TN also fell within the range of expected values for Iowa (12-67 kg TN ha⁻¹; Strock et al., 2004; Johnson et al., 1998; Sawyer et al., 2013). Initial TC in 2015 at early termination was 38% higher than in 2014, corresponding to a 40% increase in fall-to-spring GDDs at early termination from 2014 to 2015 (416 and 691 GDDs, respectively; Iowa Environmental Mesonet, 2015). Rye in 2015 achieved more fall GDDs because it was planted 6 weeks earlier in the fall than rye in the spring of 2014. Rye that is well-established in the fall grows more roots and tillers, which may give it more points of growth to take off faster in the spring. Greater fall growth may also allow it to become more cold-resistant, making it able to break dormancy faster in the spring.

Cover Crop Effects on Soil NO₃-N

Presence of rye generally decreased soil NO₃-N, similar to previous findings on cover crops (Tonitto et al., 2006; Gardner and Drinkwater, 2009; Tables 7-11), but the effect varied from 2014 to 2015. When rye was well-established in 2015, soil NO₃-N in rye treatments was on average 56% lower than NO₃-N in the no-rye treatment, a reduction within the range of previously reported reductions of NO₃-N concentrations in drainage water in Iowa (Kaspar et al., 2012; Qi et al., 2011; Kaspar et al., 2007; Strock et al., 2004). In 2014 when rye produced more growth at late termination, soil NO₃-N generally decreased, however when rye was not well-

established at early termination, no-rye treatments had lower $\text{NO}_3\text{-N}$ than rye treatments at a few dates (Figures 3-5). Soil $\text{NO}_3\text{-N}$ in 2015 may have also been reduced due to lower soil moisture through rye evapotranspiration, reducing microbial activity. The difference in soil $\text{NO}_3\text{-N}$ levels of the rye treatments from 2014 to 2015 is likely due to the establishment of the rye leading up to termination. Rye terminated at a later date accumulates much more biomass and accumulates more TN compared to rye terminated at an earlier date (Mirsky et al., 2011). Poor establishment of rye in the fall of 2013 and little growth before early termination did not accumulate enough TN for the presence of a rye cover crop to affect soil $\text{NO}_3\text{-N}$. The higher C:N ratio of the mature late-terminated rye in 2015 likely contributed to the extended period of low soil $\text{NO}_3\text{-N}$ after termination. Microbes must immobilize soil $\text{NO}_3\text{-N}$ to break down high-carbon plant residues, reducing soil $\text{NO}_3\text{-N}$ concentrations and slowing the decomposition of the plant. Increased rye biomass in 2017 likely also decreased soil temperature, and therefore microbial activity and decomposition.

It is also possible that no-rye treatment may have lost more soil $\text{NO}_3\text{-N}$ at initiation of the experiment in 2014 due to less evapotranspiration of rye, contributing to increased soil water and drainage (Qi and Helmers, 2010). Before termination, less-developed rye may not accumulate significant cover to reduce $\text{NO}_3\text{-N}$ runoff and leaching.

Although soil was not sampled between November and March, the significantly lower soil $\text{NO}_3\text{-N}$ in the fall of 2014 and 2015 in plots where rye was well established suggest strong fall establishment of rye can further extend rye's ability to capture soil $\text{NO}_3\text{-N}$ in the fall.

Rye Decomposition Rate

In this study, decomposition of TC and TN was not significantly impacted by either herbicide type or timing of termination. Since k values varied widely, and timing of termination was a significant variable to include in the regression, it may be that a study with more replicates would yield more information about the relationship between termination time and decomposition rate.

Yield

Corn and soybean yields were not affected by rye, herbicide, or timing treatment in 2014 (Table 15). Though rye sometimes reduces corn yield when terminated just before corn planting (by 7-16%; Johnson et al., 1998; Singer and Kohler, 2005; Sawyer et al., 2013; Hartzler, 2014), our results are similar to studies which suggest yields do not change with the presence of a rye cover crop if terminated ahead of corn planting (Crandall et al 2003; Tonitto et al 2006). Similar to other studies, soybean yields were not affected by presence of a rye cover crop (Ruffo et al 2004; Strock et al., 2004; De Bruin et al, 2005). Low overall grain yields in 2014 were likely due to the experimental site's recent conversion to no-till (2 years prior to initiation of experiment), late nitrogen fertilizer application, and the infestation of jackrabbits.

Conclusions

The results of this study suggest that cereal rye terminated just several days before soybean can reduce potential $\text{NO}_3\text{-N}$ export without impacting grain yield. We demonstrate the

ability of late-terminated rye to reduce soil $\text{NO}_3\text{-N}$ by 71% compared to that observed when rye was terminated several weeks before planting, regardless of fall rye establishment. However, mature, late-terminated rye biomass may not decompose fully within one season. With N recycling occurring over a multi-year period, farmers should be advised that late-terminated cover crops may necessitate altered N application over a long period of time.

Cereal rye is particularly valuable before soybeans because it can be terminated immediately before planting soybean without affecting yield. Though cereal rye is effective at reducing $\text{NO}_3\text{-N}$ concentrations before corn without affecting yield if managed properly, synchronizing N mineralization from cover crops with N uptake by grain crops in the spring can help retain $\text{NO}_3\text{-N}$ on the field during the period of high $\text{NO}_3\text{-N}$ loss in Iowa.

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Tables

Table 1. Rye and corn or soybean planting date, cover crop termination date, and nitrogen fertilizer rate for each crop system, rotation, and year.

		Crop System				
		Continuous Corn	Corn-Soybean*		Corn-Soybean	
Crop phase		Corn	Corn		Soybean	
2014	Rye termination timing	Early	Early	Late	Early	Late
	Crop seeding date	5/9	5/9	-	5/29	5/29
	Nitrogen fertilizer rate (kg N ha ⁻¹)	224	168	-	0	0
	Date of fertilizer application	7/7	7/7	-	-	-
	Date of termination	4/25	4/25	-	4/25	5/23
Crop phase		Corn	Soybean		Corn	
2015	Rye termination timing	Early	Early	Late	Early	-
	Crop seeding date	5/1/2015	5/19/2015	5/19/2015	5/1/2015	-
	Nitrogen fertilizer rate (kg N ha ⁻¹)	224	0	0	168	-
	Date of fertilizer application	6/5	-	-	6/5	-
	Date of termination	4/16	4/16	5/13	4/16	-

* In 2014, the first year of the experiment, the corn-soybean system followed corn which was grown over the whole experimental site in 2013 prior to this study.

For the 2014 season, rye was seeded on October 25th, 2013. For the 2015 season, rye was seeded September 12th, 2014.

Table 2. Biomass sampling, rye termination, and litter collection dates in 2014 and 2015. Negative days after termination indicates live biomass sampling (see methods) while positive days after termination include sampling of a litter decomposition bag.

Early termination		Late termination	
Sample date	Days after termination	Sample date	Days after termination
Rye planting: 10/25/2013			
		5/5/2014	-18
4/22/2014	-3	5/20/2014	-3
Termination date: 4/25/2014		Termination date: 5/23/2014	
4/26/2014	1	5/24/2014	1
5/5/2014	10	6/3/2014	11
5/20/2014	25	6/17/2014	25
6/3/2014	39	7/3/2014	41
6/24/2014	60	7/22/2014	60
8/4/2014	101	9/1/2014	101
Rye planting: 9/12/2014			
10/24/2014	-174	10/24/2014	-201
4/15/2015	-1	4/15/2015	-26
		5/11/2015	-2
Termination date: 4/16/2015		Termination date: 5/13/2015	
4/17/2015	1	5/15/2015	2
4/27/2015	10	5/26/2015	13
5/11/2015	24	6/8/2015	25
5/28/2015	41	6/23/2015	41
6/17/2015	61	7/13/2015	61
7/27/2015	101	8/22/2015	101

Table 3. Phosphorus, potassium, and pH concentrations as sampled per block on September 18th, 2014 (see Figure 2 and methods).

Landscape Location	Bulk Density(g/cm ³)	Phosphorus		Potassium		pH
		Mehlich-3 P (mg/kg)	Relative Level [#] Mehlich-3 P	Mehlich-3 K (mg/kg)	Relative Level [#] Mehlich-3 K	
Block 1	1.29*	65	Very high	176	Optimum	6.8
Block 2	1.29	54	Very high	200	Optimum	6.7
Block 3	1.29	33	Very high	137	Low	6.5
Block 4	1.29	60	Very high	152	Low	6.5

*Estimated from Al-Kaisi et al, 2010

[#]Relative levels are according to Iowa State University Extension recommendations (Mallarino et al, 2013).

Table 4. Initial dry mass of rye litter in each block after termination. Mass of litter within treatments was different for each block.

			Dry mass of rye litter (g/0.0625 m²)		
			Block 1	Block 2	Block 3
2014	Early	Glyphosate	0.31	0.27	0.36
		Paraquat	0.36	0.32	0.38
	Late	Glyphosate	4.43	4.60	5.81
		Paraquat	4.91	4.33	5.75
2015	Early	Glyphosate	3.96	3.44	--*
		Paraquat	3.95	3.59	4.43
	Late	Glyphosate	70.85	128.79	70.23
		Paraquat	92.50	129.02	75.11

*Dry sample spilled

Table 5. Rye cover crop dry aboveground biomass, total carbon (TC), total nitrogen (TN) and the carbon:nitrogen (C:N) ratio at early and late termination times prior to soybean planting*. Data are pooled across herbicide treatments.

		Dry biomass (kg ha ⁻¹)	TC (kg ha ⁻¹)	TN (kg ha ⁻¹)	C:N ratio
Spring 2014	Early termination	640a [†]	290a*	28a	11a
	Late termination	1200b	500b	32a	16b
Fall 2014	Early termination	130a	55a	5.9a	9.2a
	Late termination	190a	99a	10a	9.1a
Spring 2015	Early termination	1300a	470a	34a	17a
	Late termination	5900a	2700b	87a	31b

*Cover crop not sampled in fall 2013 because the fall-planted cover crop did not germinate until spring 2014

[†]Means with the same letter within a column and season are not different ($P \leq 0.05$).

Table 6. Rye cover crop dry belowground biomass, total carbon (TC), total nitrogen (TN) and the carbon:nitrogen (C:N) ratio at early and late termination times prior to soybean planting in spring 2014*. Data are pooled across herbicide treatments.

	Dry Biomass (kg ha⁻¹)	TC (kg ha ⁻¹)	TN (kg ha ⁻¹)	C:N ratio
Early termination	5.21a ⁺	0.07a	0.02a	20a
Late termination	8.71a	3.09b	0.11b	27a

*Cover crop not sampled in fall 2013 because the fall-planted cover crop did not germinate until spring 2014. Root biomass was not sampled in fall 2014.

⁺Means with the same letter within a column are not different ($P \leq 0.05$).

Table 7. Probability values (P>F) from repeated measures ANOVA for herbicide effects on soil NO₃-N concentration between cover crop and herbicide treatments in the continuous corn system in 2014. Corn was planted on May 9, 2014.

Treatment	P > F	Contrasts within date				
		May 10	May 14	May 22	June 24	October 30
Date	<0.01					
Herbicide ⁺	<0.01					
Date*Herbicide	<0.01					
Glyphosate versus No rye	0.31	0.91	0.16	0.04	0.73	<0.01
Glyphosate versus Paraquat	0.02	0.03	0.50	<0.01	0.05	0.27
Paraquat versus No rye	<0.01	0.23	0.02	0.51	0.39	<0.01

⁺The main effect of herbicide compares paraquat, glyphosate, and no rye termination treatments; 'No rye' refers to plots without cover crop; paraquat and glyphosate herbicide treatments were applied to plots with cover crop.

Table 8. Probability values (P>F) from repeated measures ANOVA for herbicide and termination timing effects on soil NO₃-N concentration in the soybean phase of the corn-soybean system in 2014. Soybean was planted on May 29, 2014.

Treatment	P > F	Contrasts within date				
		May 14	May 22	May 30	June 24	Oct 30
Termination timing [‡]	<0.01					
Date	<0.01					
Date*Termination timing	<0.01					
Early versus Late	0.09	<0.01	<0.01	0.05	0.94	0.054
Early versus No rye	0.97	0.09	0.01	0.98	0.12	<0.01
Late versus No rye	0.09	0.54	<0.01	0.11	0.07	<0.01
Herbicide ⁺	0.28					
Date*Herbicide	0.06					

[‡]The main effect of termination timing compares early, late, and no rye termination timing treatments; ‘No rye’ refers to plots without cover crop; early and late termination timing treatments were applied to plots with cover crop.

⁺The main effect of herbicide compares paraquat, glyphosate, and no rye termination treatments; ‘No rye’ refers to plots without cover crop; paraquat and glyphosate herbicide treatments were applied to plots with cover crop.

Table 9. Probability values (P>F) from repeated measures ANOVA for herbicide effects on soil NO₃-N concentration between cover crop and herbicide treatments in the continuous corn system in 2015. Corn was planted on May 1, 2015.

Treatment	P > F	Contrasts within date				
		April 3	April 17	April 27	May 6	May 28
Date	<0.01					
Herbicide ⁺	0.02					
Date*Herbicide	0.05					
Glyphosate versus No rye	0.02	<0.01	0.01	0.11	<0.01	<0.01
Glyphosate versus Paraquat	0.94	0.86	0.98	0.06	0.46	0.35
Paraquat versus No rye	0.03	<0.01	<0.01	0.02	0.03	0.07

⁺The main effect of herbicide compares paraquat, glyphosate, and no rye termination treatments; 'No rye' refers to plots without cover crop; paraquat and glyphosate herbicide treatments were applied to plots with cover crop.

Table 10. Probability values (P>F) from repeated measures ANOVA for herbicide and termination timing effects on soil NO₃-N concentration in the soybean phase of the corn-soybean system in 2015. Soybean was planted on May 19, 2015.

Treatment	P > F	Contrasts within date								
		April 17	April 27	May 6	May 12	May 19	May 28	June 2	June 18	Nov 2
Termination timing [‡]	<0.01									
Date	<0.01									
Date*Termination timing	<0.01									
Early versus Late		0.01	0.49	0.05	0.02	<0.01	<0.01	<0.01	<0.01	0.11
Early versus No rye		0.20	0.12	<0.01	0.11	0.35	0.26	0.91	0.40	<0.01
Late versus no rye		<0.01	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.02
Herbicide ⁺	0.18									
Termination timing*Herbicide	0.24									
Date*Herbicide	0.85									

[‡]The main effect of terminating timing compares early, late, and no rye termination timing treatments; 'No rye' refers to plots without cover crop; early and late termination timing treatments were applied to plots with cover crop.

⁺The main effect of herbicide compares paraquat, glyphosate, and no rye termination treatments; 'No rye' refers to plots without cover crop; paraquat and glyphosate herbicide treatments were applied to plots with cover crop.

Table 11. Probability values (P>F) from repeated measures ANOVA for herbicide and termination timing effects on soil NO₃-N concentration in the corn phase of the corn-soybean system in 2015. Corn was planted on May 1, 2015.

Treatment	P > F	Contrasts within date						
		March	April	April	May	May	June	Aug
		27	17	27	6	19	18	12
Date	<0.01							
Herbicide ⁺	0.06							
Date*Herbicide	<0.01							
Glyphosate versus No rye	0.11	<0.01	0.02	0.02	<0.01	0.01	0.08	0.71
Glyphosate versus Paraquat	0.17	0.94	0.43	0.06	0.25	0.42	0.14	0.03
Paraquat versus No rye	0.59	<0.01	0.10	<0.01	<0.01	0.05	<0.01	0.46

⁺The main effect of herbicide compares paraquat, glyphosate, and no rye termination treatments; 'No rye' refers to plots without cover crop; paraquat and glyphosate herbicide treatments were applied to plots with cover crop.

Table 12. Probability values (P>F) from repeated measures ANOVA for effects and contrasts on aboveground total carbon (TC), total nitrogen (TN) and carbon:nitrogen (C:N) ratio in the soybean phase of the corn-soybean. Contrasts of significant termination timing and herbicide interactions are shown (p<0.1). Date is nested within termination timing.

Year	Treatment	TC	TN	C:N ratio
2014	Termination timing [‡]	<0.01	<0.01	<0.01
	Herbicide ⁺	0.93	0.52	<0.01
	Glyphosate versus Paraquat	*	*	<0.01
	Termination timing*Herbicide	0.99	0.93	0.72
	Date	<0.01	<0.01	<0.01
	Early versus Late	<0.01	<0.01	<0.01
	Herbicide*Date	0.81	0.94	0.35
2015	Termination timing	<0.01	<0.01	<0.01
	Herbicide	0.26	0.51	0.71
	Termination timing*Herbicide	0.28	0.34	0.91
	Date	<0.01	<0.01	<0.01
	Early versus Late	<0.01	<0.01	<0.01
	Date*Herbicide	0.94	0.68	0.94

[‡]The main effect of terminating timing compares early, late, and no rye termination timing treatments; ‘No rye’ refers to plots without cover crop; early and late termination timing treatments were applied to plots with cover crop.

⁺The main effect of herbicide compares paraquat, glyphosate, and no rye termination treatments; ‘No rye’ refers to plots without cover crop; paraquat and glyphosate herbicide treatments were applied to plots with cover crop.

*Biomass values were unavailable for all paraquat values in 2014.

Table 13. Probability values (P>F) from repeated measures ANOVA for herbicide and termination timing effects and contrasts on total carbon (TC), total nitrogen (TN) and carbon:nitrogen (C:N) ratio of belowground rye biomass in the soybean phase of a corn-soybean system. Contrasts of significant termination timing and herbicide interactions are shown (p<0.1).

Treatment	TC	TN	C:N ratio
Termination timing [‡]	0.48	0.30	0.08
Herbicide [‡]	0.08	0.13	0.41
Termination timing*Herbicide	0.40	0.35	0.77
Date(Termination timing)	0.17	0.58	<0.01
Early versus Late	0.08	--	0.08
Date*Herbicide(Termination timing)	0.90	0.89	0.43

[‡]The main effect of terminating timing compares early and late rye termination timing treatments; early and late termination timing treatments were applied to plots with cover crop; plots without cover crop were not sampled for rye biomass.

[‡]The main effect of herbicide compares paraquat and glyphosate termination treatments; paraquat and glyphosate herbicide treatments were applied to plots with cover crop; plots without cover crop were not sampled for rye biomass.

Table 14. Estimates of decomposition rate (k) from asymptotic regression at early and late termination times, and probability values ($P > F$) from Welch's t-test comparing the effect of termination times on the k of TC and TN remaining in a decomposing rye litterbag study.

		2014			2015		
		Early	Late	$P > F$	Early	Late	$P > F$
Avg k	TC	0.03	0.05	0.38	0.05	0.05	0.99
	TN	0.04	0.06	0.46	0.06	0.05	0.73

Table 15. Corn and soybean yields at the field site harvested October 25th, 2014 and November 2nd, 2015 as a function of termination timing of rye. There were no significant differences among treatments in either year.

		Yield with no rye cover crop (kg ha ⁻¹)	Yield with early-terminated rye (kg ha ⁻¹)		Yield with late-terminated rye (kg ha ⁻¹)	
Year	Herbicide	-	Glyphosate	Paraquat	Glyphosate	Paraquat
2014	Corn	7270	7300	6800	-	-
	Soybean	1720	2030	2400	1740	2040
2015	Corn	11700	1120	1120	-	-
	Soybean	3260	2960	3000	2800	2850°

Figures

Figure 1. Daily precipitation and cumulative rye growing degree days (GDD, rye base = 0°C) in 2014, 2015, and the 30-year GDD average for corresponding rye seeding dates in Boone, Iowa.

? North	15.2m	12.2m					
12.2m	C-S N None	16 rows	C-S E Glyphosate		S-C N None		C-S E Paraquat
	C-S N None		C-S E Paraquat		S-C N None		C-S E Glyphosate
6.1m	S-C E Glyphosate	8 rows	C-S L Paraquat		C-S N None	Block 2	S-C E Glyphosate
	S-C E Paraquat		C-S L Glyphosate		C-S N None		S-C E Paraquat
	S-C E Paraquat	Block 1	S-C N None		C-C N None		S-C E Paraquat
	S-C E Glyphosate		S-C N None		C-C N None		S-C E Glyphosate
	C-C N None		C-C E Paraquat		C-C E Glyphosate		C-S L Paraquat
	C-C N None		C-C E Glyphosate		C-C E Paraquat		C-S L Glyphosate
	C-C N None	Block 3	C-S L Glyphosate		S-C E Paraquat	Block 4	C-C N None
	C-C N None		C-S L Paraquat		S-C E Glyphosate		C-C N None
	C-S N None		C-S E Paraquat		C-S L Glyphosate		C-S E Glyphosate
	C-S N None		C-S E Glyphosate		C-S L Paraquat		C-S E Paraquat
	S-C E Paraquat		S-C N None		C-C E Paraquat		S-C N None
	S-C E Glyphosate		S-C N None		C-C E Glyphosate		S-C N None
	C-C E Paraquat		S-C E Paraquat		C-S N None		S-C E Paraquat
	C-C E Glyphosate		S-C E Glyphosate		C-S N None		S-C E Glyphosate

Figure 2. Layout of experimental plots in 2015. A continuous corn (C-C) or corn (C)-soybean (S) system was planted. Corn-soybean plots were planted either with corn in 2014 and soybean in 2015 (C-S), or soybean in 2014 and corn in 2015 (S-C). Each plot (12.2 x 15.4 m) contains either a rye cover crop, or no rye cover crop. Each plot is split into two subplots by herbicide type: where a rye cover crop is present, rye in subplots is terminated with either paraquat or glyphosate. In control plots without a rye cover crop, no herbicide is applied. Rye is terminated at one of two dates: early termination (E) before planting corn, or late termination (L) before planting soybeans. All plots in the corn phase are terminated at the early date. Plots without a rye cover crop are not terminated (N). Shaded areas represent alleys maintained in mowed lawn grass. Prior to the experiment, all plots were planted with corn in 2013.

Figure 3. Soil nitrate-N in a continuous corn rotation in 2014 and 2015. Significant differences: asterisks (*) indicate an effect of cover crop presence and herbicide treatment ($p < 0.1$). Prior to spring termination, samples were taken by subplot. The first sample date in 2014 is not connected to the second because $\text{NO}_3\text{-N}$ samples were taken from plots, not subplots. Subplots had not been treated differently before termination. (a) 2014, (b) 2015.

Figure 4. Soil nitrate-N in the soybean year of a corn-soybean rotation in 2014 and 2015 as a function of rye and two termination times. Significant differences: crosses (+) indicate an effect of rye termination timing treatment ($p < 0.1$). There were no interactive effects of herbicide and rye termination timing treatment. The first sample date in 2014 is not connected to the second because $\text{NO}_3\text{-N}$ samples were taken from plots, not subplots. Subplots had not been treated differently before termination. (a) 2014, (b) 2015.

Figure 5. Soil nitrate-N in the corn year of corn-soybean rotation in 2015 as a function of rye and two herbicide treatments. Significant differences: asterisks (*) indicate an effect of herbicide treatment ($p < 0.1$).

Figure 6. Total rye aboveground carbon in a litter decomposition experiment as a function of two termination times and two herbicide treatments. (a) 2014, (b) 2015.

Figure 7. Total rye aboveground nitrogen in a litter decomposition experiment as a function of two termination times and two herbicide treatments. Biomass in 2015 is much greater due to strong rye establishment the previous fall. (a) 2014, (b) 2015.

Figure 8. Ratio of carbon to nitrogen in a rye aboveground litter decomposition experiment as a function of two termination times and two herbicide treatments. (a) 2014, (b) 2015.

CHAPTER 3. GENERAL CONCLUSIONS

Investigating best cover crop management practices for nutrient retention is essential to increasing cover crop adoption and minimizing the leaching of soil $\text{NO}_3\text{-N}$ and rye decomposition over time. The study presented in Chapter 2 explored the effects of rye termination timing and herbicide type on soil $\text{NO}_3\text{-N}$ and rye decomposition over time. While cover crop research has focused largely on the effects of cover crop planting date and termination date on yield, the present research aimed to determine efficacy of cover crops at reducing soil $\text{NO}_3\text{-N}$ and subsequent return of N to soil.

Results suggest that terminating rye as late as possible before soybean planting makes cover crops more effective at immobilizing N without impacting yield. Consistent with previous studies, soil with rye averaged 30% less $\text{NO}_3\text{-N}$ content than soil with no rye on dates when soil $\text{NO}_3\text{-N}$ differed between rye and no rye cover. These differences lasted for 1-3 weeks after termination, depending on rye biomass. Our study found that more N is sequestered and N loss is slower from late-terminated relative to early-terminated rye; however, multi-year studies of litter decomposition and N loss are needed to better predict in-field N turnover with cover crops of different growth stages. We have insufficient evidence to reject the hypothesis that herbicide type does not affect rye N loss or soil $\text{NO}_3\text{-N}$, but further studies on herbicide effect on root decomposition, which should theoretically be impacted differentially by herbicide, are necessary. Our research suggests seeding rye earlier in the fall can increase spring rye growth, further contributing to late-terminated rye's impact on soil $\text{NO}_3\text{-N}$ uptake during the critical leaching period in spring, as well as reducing soil $\text{NO}_3\text{-N}$ in the fall. Our study provides more assurance to time-strapped farmers that staggering cereal rye termination will give them more flexibility,

while waiting to terminate rye before soybeans are planted will maximize the benefits cereal rye provides, by reducing soil $\text{NO}_3\text{-N}$ in the spring and releasing it back to crops after termination without affecting crop yield.