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IMPACTS OF INTENSIFYING A CORN-SOYBEAN ROTATION WITH WINTER WHEAT (TRITICUM AESTIVUM) ON NUTRIENT LEACHING, PLANT AVAILABLE NUTRIENTS, CROP YIELDS, AND NITROGEN DYNAMICS IN SOUTHERN ILLINOIS

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by

Abigail Spiers

B.S., Northland College, 2021

A Thesis
Submitted in Partial Fulfillment of the Requirements for the
Master of Science Degree

School of Forestry and Horticulture
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THESIS APPROVAL

IMPACTS OF INTENSIFYING A CORN-SOYBEAN ROTATION WITH WINTER WHEAT (*TRITICUM AESTIVUM*) ON NUTRIENT LEACHING, PLANT AVAILABLE NUTRIENTS, CROP YIELDS, AND NITROGEN DYNAMICS IN SOUTHERN ILLINOIS

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A Thesis Submitted in Partial
Fulfillment of the Requirements
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Master of Science
in the field of Forestry

Approved by:
Dr. Karl W.J. Williard, Chair
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June 5, 2024

AN ABSTRACT OF THE THESIS OF

Abigail Spiers, for the Master of Science degree in Forestry, presented on June 5, 2024, at Southern Illinois University Carbondale.

TITLE: IMPACTS OF INTENSIFYING A CORN-SOYBEAN ROTATION WITH WINTER WHEAT (*TRITICUM AESTIVUM)* ON NUTRIENT LEACHING, PLANT AVAILABLE DYNAMICS, CROP YIELDS, AND NITROGEN DYNAMICS IN SOUTHERN ILLINOIS

MAJOR PROFESSOR: Dr. Karl W.J. Williard

The Midwestern United States is a nationally and globally important producer of agricultural products and uses intensive practices to achieve high grain yields. However, intensive agriculture is a major contributor of nitrogen and phosphorus export to the Mississippi River and the hypoxic zone in the Gulf of Mexico. Cover cropping is a recommended conservation practice for providing soil cover throughout the winter and taking up nutrients that may otherwise be lost in bare fallow systems, but the associated costs limit widespread adoption of this practice. Double cropping, which involves growing two crops in one year, is functionally similar to cover cropping and can be harvested for an additional income, but the water quality impacts of applying fertilizer to maximize yields and the systemic impacts of intensification with another crop on corn-soybean rotations are not well understood. This two-year, plot scale study in Carbondale, Illinois was designed to assess nutrient leaching, referring to nitrate-N, ammonium-N, and dissolved reactive phosphorus (DRP), nutrient availability, and crop yields when using bare fallow, cereal rye (S*ecale cereale*) cover crops, or winter wheat (*Triticum aestivum*) double crops with varying nitrogen fertilizer rates and timings in the winter seasons of corn-soybean rotations. Four blocks with randomly assigned treatments comprised of two treatment factors were used. These treatment factors included rotations with either bare fallow or cover crops in alternate winters and winter wheat fertilizer management intensity with a high fertilizer treatment level, grower recommended rates applied at planting, tillering, and jointing, a medium fertilizer treatment level, grower recommended rates applied at tillering and jointing, a low fertilizer treatment level, with reduced nitrogen rates applied at tillering and jointing, and a no fertilizer treatment level, which was used as either corn-soybean or corn-cover crop-soybean-cover crop control.

Additional nutrient inputs from fertilizers in the winter wheat seasons did not significantly increase nitrate-N, ammonium-N, or DRP leaching in the 2021-2022 winter wheat sampling season and nitrate-N and ammonium-N leaching was significantly less in some or all the winter wheat plots compared to the control plots. Winter wheat yields and nitrogen uptake in 2022 were significantly greater in medium fertilizer plots while yield-based nitrogen leaching and partial nitrogen balances were significantly greater in high fertilizer treatments, indicating that delayed fertilization in winter wheat can improve nitrogen use efficiency and yields. Soybean yields were significantly greater in plots without winter wheat due to a longer growing season, but plant available ammonium-N concentrations, which were greater in winter wheat plots, also had a significant negative relationship with soybean yields, indicating that this may have impeded biological nitrogen fixation. Using cover crops in alternate winters reduced nitrate-N leaching by 106% and plant available nitrate-N concentrations by 107% in the season as well as the subsequent corn season by 66% and 90%, respectively, compared to the bare fallow plots, and the decreased plant available nitrate-N concentrations in cover crop plots caused a 6% yield penalty in the corn harvest. Despite yield penalties to cash crops from winter crops, the use of double crops was the only factor that significantly impacted total crop yields. The use of cover crops in alternate winters was the most significant factor in nutrient leaching, demonstrating that these practices can be used to increase total crop yields without contributing significantly to nutrient export. For farmers concerned with the costs of cover cropping, double cropping is a practice that can provide some of the same ecosystem services while also providing an additional financial incentive.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

INTRODUCTION

Agriculture is an important industry and way of life in the US, but unintended consequences of agricultural practices are often detrimental to the environment. High amounts of precipitation in much of the Mississippi River Basin (MRB) along with the region's temperate climate (Andresen et al., 2012) has created an ideal environment for farming. Because of this, the MRB has been marked by land use changes largely related to development and agriculture, leading to roughly 65% of the land being converted to farmland with 25% being harvestable cropland (Turner & Rabalais, 2003). Given that this farmland contributes over 80% of the corn (*Zea mays*) and soybeans (*Glycine max*) to the country's total production of these commodities (Basche et al., 2015), which makes up over one third of the world's total production (FAO, 2020), it has become both a nationally and internationally important resource (Hatfield, 2012). As populations continue to rise, food security becomes an even more pressing concern (FAO et al., 2023; Searchinger et al., 2019; Tilman et al., 2011) and by 2050, food production will need to increase by at least 35% (Van Dijk et al., 2021). However, intensive agriculture causes sustainability issues that also need to be addressed (Matson et al., 1997).

With fertilization adding more nutrients than would naturally be available, especially if there is not vegetation to remove them, agriculture is a main source of nutrient losses to water systems (Carpenter et al., 1998). Excess nutrients are the second and third most prevalent source of impairment in lakes and streams, respectively (Hellerstein et al., 2019), and the production of corn and soybeans alone are estimated to contribute the highest amount of nitrogen, 52%, and the second highest amount of phosphorus, 25%, being delivered to the MRB (Alexander et al., 2007). The impacts of reactive nitrogen in particular are even ranked as one of the five “emerging issues of environmental concern” most recently reported by the United Nations Environmental Programme ([UNEP], 2019). As a water-soluble compound, nitrate is most often associated with nitrogen losses by leaching from the soil, which can cause groundwater and surface water contamination (Cameron et al., 2013; Dinnes et al., 2002; Rudolph et al., 2015). While the impact of dissolved reactive phosphorus (DRP) leaching is not well understood and thought to be minor compared to losses of particulate phosphorus (Illinois Nutrient Loss Reduction Strategy [NLRS], 2015), leaching has been shown to be an important source of phosphorus losses in soils that are sandy, high in organic matter, or high in legacy phosphorus (Sims et al., 1998; Kronvang et al., 2007), especially when considering bioavailable sources of phosphorus (Baker et al., 2014).

Agricultural production and resource efficiency will need to increase to keep up with growing food demand, but expansion and intensification of agricultural land each come with their own sustainability issues, so increasing the ecosystem services provided by existing food production areas is more important than ever (Foley et al, 2005; Foley et al., 2011). Cover cropping is often considered one of the most effective in-field methods of reducing nutrient losses (NLRS, 2015), and while its adoption in the U.S. is growing, it is estimated to be used on less than 5% of the country’s cropland (Wallander et al., 2021). Farmers that do not use cover crops often report concerns with the potential financial losses of using cover crops, either directly, by investing time and money into planting a crop they cannot sell, or indirectly, by having reduced yields in their cash crops (Sustainable Agriculture Research and Education [SARE], 2020). Producing two cash crops in one year, called double cropping, is a form of agricultural intensification in which farmers can profit rather than lose money on winter cover. This can provide the same physical benefits to the soil as cover cropping while also increasing food production with the same amount of area, though the effects of using chemical fertilizers to enhance yields is still not fully understood (Borchers et al., 2014). While the use of fertilizers is needed to maximize winter wheat production, it may also increase nitrogen losses if more nitrogen is applied through fertilization than is being removed by crops.

Following other studies at Southern Illinois University Carbondale also funded by the Illinois Nutrient Research and Education Council (NREC), this study continues to seek sustainable agricultural practices that will benefit water quality in a feasible way. Our goal is to determine the effectiveness of winter wheat (*Triticum aestivum*) as a double crop to prevent excess nutrient leaching compared to a cereal rye (*Secale cereale*) cover crop or no winter ground cover. Varying fertilizer treatments, based on NREC grower recommendations, are also used to determine the impacts of fertilizer amounts and timing on nutrient leaching, nutrient availability in soil, crop yields, and nitrogen dynamics.

OBJECTIVES

1. Assess nitrate-N, ammonium-N, and dissolved reactive phosphorus (DRP) leaching in soil water, nitrate-N, ammonium-N, and DRP availability in soil solution, nitrogen uptake by cash crops and winter crops, and agronomic nitrogen balances among corn-soybean rotations with bare fallow (control), cereal rye cover crop (recommended nutrient reduction scenario), and winter wheat (double cropping scenario) with bare fallow or a cereal rye cover crop.

- Hypothesis: Nitrate-N, ammonium-N, and DRP leaching in soil water will be lowest in cereal rye cover crop and greatest in bare fallow rotations due to the lack of removal by crops. Nitrate-N, ammonium-N, and DRP availability in soil solution will be lowest in cereal rye cover crop and greatest in bare fallow rotations. Nitrogen uptake in cash crops will be lowest in cereal rye cover crop and greatest in winter wheat with bare fallow rotations. Nitrogen uptake in winter crops will be greater in winter wheat than cereal rye cover crop. Agronomic nitrogen balance will be lowest in cereal rye cover crop and greatest in winter wheat with bare fallow rotations.

2. Determine effects of high, medium, and low intensity nitrogen fertilizer treatments for winter wheat on nitrate-N, ammonium-N, and DRP leaching in soil water, nitrate-N, ammonium-N, and DRP availability in soil solution, nitrogen uptake by cash crops, and agronomic nitrogen balances.

- Hypothesis: Nitrate-N, ammonium-N, and DRP leaching in soil water will be lowest in low intensity fertilizer treatments and greatest in high intensity fertilizer treatments. Nitrate-N, ammonium-N, and DRP availability in soil solution will be lowest in low intensity fertilizer treatment and greatest in high intensity fertilizer treatments. Nitrogen uptake in cash crops will be lowest in low intensity fertilizer treatments and greatest in medium intensity fertilizer treatments due to increased nutrient availability when nutrient requirements are higher. Agronomic nitrogen balances will be lowest in low intensity fertilizer treatments and greatest in high intensity fertilizer treatments.

3. Assess cash crop and double crop (cash crop and winter wheat) grain yields and yield-based N losses in corn-soybean rotations with bare fallow, cereal rye cover crop, and winter wheat with bare fallow or cereal rye cover crop.

- Hypothesis: Cash crop grain yields will be lowest in cereal rye cover crop and greatest in bare fallow rotations. Double crop grain yields will be greatest in winter wheat with bare fallow and lowest in cereal rye cover crop rotations. Yield-based N losses will be lowest in winter wheat with cereal rye cover crop and greatest in bare fallow rotations.

4. Determine effects of high, medium, and low intensity fertilizer treatments for winter wheat on cash crop and double crop grain yields and yield-based N losses.

- Hypothesis: Cash crop yields will be lowest in low intensity fertilizer treatments and greatest in medium intensity fertilizer treatments due to the increased nutrient inputs closer to cash crop planting. Double crop yields will be lowest in low intensity fertilizer treatments and greatest in high intensity fertilizer treatments. Yield-based N losses will be lowest in low intensity fertilizer treatments and greatest in high intensity fertilizer treatments.

LITERATURE REVIEW

BACKGROUND

AGRICULTURAL INTENSIFICATION

Advancement in agricultural technology results in agricultural intensification, a process that increases crop yields without requiring more space. Agricultural intensification has become more extreme over time since the European colonization of the United States, beginning with major land conversions and a large population of farmers then transitioning to more mechanized and productive systems (Zynda, 2022). Since the mid-20th century alone, the amount of land and labor required has decreased by over 25 and 75 percent, respectively, while outputs have increased almost three times (Njuki, 2020). Although agricultural intensification has been tied to human populations for as long as agriculture has been around (Milner & Boldsten, 2022), modern agricultural advances have caused populations to skyrocket. As an example, synthetically produced ammonia alone is estimated to support about half of the population through increases in crop yields (Erisman et al., 2008). The processes that have made this possible, however, also have human health, environmental, and economic consequences, and while continued intensification will almost certainly be necessary to keep up with even greater future populations, finding more sustainable methods is needed to minimize these consequences (Matson et al., 1997; Tscharntke et al., 2012).

FERTILIZER MANAGEMENT

Easy access to affordable fertilizer was a major contributor to the extensive agricultural intensification in the past century. Nitrogen and phosphorus are the most important for maintaining high crop yields, but also cause environmental problems when applied in excess (Lu & Tian, 2017). Before these problems became apparent, economics was the main factor that drove research into finding optimal fertilizer application rates in the mid-1900's (Nafziger, 2021). Yield-based nitrogen management was created to simplify the complexities of nutrient management by finding a way to calculate nitrogen fertilizer needs based on the optimal yields for a field. It has been demonstrated that this method is overly generalized in a way that makes it largely inaccurate, and though many management tools still rely on this method, some are beginning to use more reliable alternatives (Rodriguez et al., 2019). Soil testing has long been the standard for quantifying phosphorus and using Bray 1 or Melich 3 is still an accepted method to determine phosphorus fertilizer recommendations (Hopkins & Hansen, 2019).

NUTRIENT CYCLES

Nitrogen

Despite being the most abundant element above the Earth’s surface, nitrogen is naturally a limiting nutrient to many ecosystems. In the absence of anthropogenic processes, the nitrogen cycle is almost entirely carried out through microbial processes (Stein & Klotz, 2016). Most nitrogen is introduced into natural systems through biological nitrogen fixation (BNF) (Galloway et al., 2004), in which free-living microbes or those in symbiotic relationships with plants, mostly legumes, activate dinitrogen (N_2) gas by breaking the triple bond between the atoms, a very energy-intensive process, which can then react with hydrogen. It can also be recycled from other organic matter such as amino acids ($R\text{-}NH_2$) in the system. These reduction processes, known as ammonification, produce ammonia (NH_3) and ammonium (NH_4^+), and nitrification can oxidize these cations to produce nitrite (NO_2-) and nitrate (NO_3-). These ions are known as reactive nitrogen because they can be taken up by plants, but nitrate and ammonium are the main forms that plants use, nitrate being the most plentiful in soils (Delwiche, 1970). Nitrogen is primarily lost from a system through denitrification, in which nitrite and nitrates are reduced to gases such as dinitrogen or nitrous oxide (N_2O), through ammonia volatilization, in which ammonium is reduced to ammonia that is then offgassed, through nitrate leaching, in which nitrate is dissolved in water and moves past the root zone in the soil profile (Cameron et al., 2013), and through annamox, in which ammonium is oxidized to dinitrogen (Stein & Klotz, 2016). Immobilization can also make nitrogen temporarily unavailable to plants because it is taken up by microbes, and mineralization, another name for the second form of ammonification mentioned above, releases reactive inorganic forms back into the system (Bruun et al., 2006).

Phosphorus

Phosphorus, the other major limiting nutrient, originates mostly from mineral sources and is naturally cycled in soil through both biotic and abiotic processes. Most phosphorus originates from minerals like apatite that contain a phosphate (PO_4^{-3}) anion and the weathering of these minerals is what allows the phosphate to be released into soil pores. These primary mineral sources are defined as refractory because they are not bioavailable. Labile forms of phosphorus can be released into the soil solution over shorter periods and are then available for plant uptake or lost to leaching. These stores include inorganic forms that can easily adsorb onto particles of clay and organic matter due to phosphate's high negative charge, as well as organic forms that are immobilized by microbes (Filippelli, 2002). These labile stores of phosphate are released into the soil solution through desorption and mineralization, both of which are heavily influenced by soil conditions; the chemical composition of the soil is especially important in adsorption-desorption cycles while physical properties such as temperature and moisture also help determine how active the microbial communities responsible for immobilization-mineralization cycles are (Mackey & Paytan, 2009). Soil solution stores of phosphate, which are immediately available to plants, are low and largely controlled by the sorption properties of the soil, but plants and symbiotic mycorrhizal fungi can produce compounds to facilitate their release from labile stores (Ruttenberg, 2003), with phosphatase being the most notable (Filippelli, 2002). Phosphorus can also be precipitated out when there is a saturation of phosphorus and another reactant in the soil solution, which is primarily calcium (Ca^{2+}) in basic soils but can also include aluminum (Al^{3+}) and/or iron (Fe^{3+}) in acidic soils (Penn & Camberato, 2019). These occluded forms are another source of refractory phosphates and must go through another weathering process to become labile. While soils make up an important store of phosphorus, it is limited by its lack of reactive forms (Filipelli, 2002).

FERTILIZER USE

Humans have been altering nutrient cycles by using manure and minerals, growing legumes that fix nitrogen, and adding phosphorus-rich bone meal to boost soil fertility for much of agriculture's history, but these alterations have become much more extreme. Modern industrialized fertilizer production can be traced to the mid-1800s, and phosphate mining followed shortly after, becoming the world's main source of phosphorus fertilizer (Samreen & Kausar, 2019). In the 1930's, the Haber-Bosch process was developed to create synthetic nitrogen fertilizer on a large scale by using high temperature and pressure and an iron catalyst to force a reaction between dinitrogen and dihydrogen (H_2) gases to produce ammonia (Erisman et al., 2008), which now makes up the largest anthropogenic addition of nitrogen (Galloway et al., 2004). The Green Revolution in the mid-1900s caused a substantial growth in fertilizer use. Between 1961 and 2013 consumption of fertilizers increased by a factor of 9.5 for nitrogen fertilizers and 3.8 for phosphorus fertilizers, but this consumption is not equally distributed; six countries make up 63% of global fertilizer use with the U.S. alone making up about 10% (Lu & Tian, 2017), which creates problems with poor fertility in some regions and nutrient pollution in others, including the U.S. (Stevens, 2019).

NUTRIENT POLLUTION

The increase in fertilizer use and its management over the past century has created many issues. Anthropogenic nitrogen sources are now greater than natural sources, more than doubling the amount of nitrogen that is being cycled naturally (Stevens, 2019), and phosphorus loading from soils to water has also more than doubled, with agriculture making up an estimated 38% of the global load (Mekonnen & Hoekstra, 2018). As of 2014, it is estimated that 60% of global nitrogen and 48% of the global phosphorus being applied to major crops are lost, 11% and 4% of which, respectively, come from the United States (West et al., 2014). Reactive nitrogen is of particular concern because it is highly mobile and can take many forms, allowing one atom to cycle through many different systems, a process known as the nitrogen cascade (Galloway, 1998). Despite the importance of nitrogen and phosphorus in living organisms, unnaturally high levels create problems with all the pillars of sustainability- societal, environmental, and economic.

Human Health

Human health is an important risk factor regarding excess nutrient pollution. The main concern regarding nitrate contamination is methemoglobinemia in infants under three months old, also called ‘blue baby syndrome.’ This condition causes nitrate to be reduced to nitrite, which impacts oxygen transport and can lead to cyanosis or, in more extreme instances, asphyxia (WHO, 2003). For this reason, the nitrate maximum contaminant level (MCL) guideline in the U.S. is 10 mg/L of nitrate-N and the World Health Organization’s is 50 mg/L of nitrate. More studies have been published since this guideline was created that may show a correlation between nitrate in drinking water and certain cancers, thyroid diseases, and birth defects, in some cases with nitrate levels below regulatory limits, but more research needs to be done to substantiate these claims (Ward et al., 2018). Due to its high solubility, nitrate is most often associated with groundwater contamination. In the MRB, there is a greater concentration of areas that are susceptible to groundwater nitrate levels greater than 4 mg/L than the rest of the U.S. with the corn belt region containing the highest concentration of high-risk areas (Nolan et al., 2002). Nitrate contamination is not limited to groundwater, however, and can raise nitrate loads above regulatory limits in rivers as well (Turner & Rabalais, 2003).

While phosphorus pollution does not have any direct health effects, eutrophication from excess nutrients in surface water can lead to harmful algal blooms (HABs), some of which may contain algae that produce toxins. Direct skin contact with water affected by HAB toxins can lead to skin irritation and those near affected water can develop respiratory problems from inhaling aerosolized particles. The greatest threat from HABs, however, comes from ingesting toxins. The risk of contamination in desalinated water is becoming more of a threat, but the consumption of aquatic animals is the most common method of ingesting these toxins, which may cause serious health effects that can even lead to death. Monitoring HABs has helped prevent contaminated foods from reaching the public, but it will become more difficult as HABs become more widespread and new toxins are discovered, especially since these toxins can bioaccumulate and affected organisms may not be detected (Berdalet et al., 2016). Research on the health effects of HABs has increased in recent decades, indicating more awareness of this problem (Young et al., 2020), and climate change will likely result in HABs that are greater in number and severity (Moore et al., 2008)

Environmental Issues

The environmental impacts of excess nutrient pollution can no longer be overstated, and water quality issues are at the forefront of these concerns. Eutrophication, a process in which photosynthesizer populations grow to an unsustainable level that depletes resources such as sunlight and oxygen, can be a natural process or one facilitated by humans, called cultural eutrophication (Chislock et al., 2013). This process can decrease the pH and amount of dissolved oxygen to levels that are dangerous for some species, and the depletion of necessary resources can shift trophic assemblages in undesirable ways, favoring unpalatable or even toxic species (Rathore et al., 2016; Smith et al., 1999). As previously stated, HABs can result from eutrophic conditions, and while toxins from HABs may bioaccumulate without affecting the aquatic species that are exposed to certain toxins (Berdalet et al., 2015), other toxins are responsible for significant fish kill events (Brooks et al., 2015). In the most extreme cases, overproduction of phytoplankton can lead to hypoxic zones, one of the largest and most famous being the Gulf of Mexico Hypoxic Zone (Rabalais & Turner, 2019). The link between increased nutrient loading from the MRB has long been linked to hypoxia in the Gulf of Mexico (Rabalais et al., 1996), much of which is found to be associated with agriculture, especially in the Midwest (Goolsby & Battaglin, 2001). Beginning in the 1950's as a seasonal occurrence, hypoxic conditions in bottom-waters of the Gulf of Mexico now persist throughout most of the year and are trending towards becoming a more permanent and extensive area that continues to alter already strained coastal ecosystems. Despite efforts to reduce nutrient loading from the Mississippi River and to reduce size of the hypoxic zone, the lack of improvements indicates that more needs to be done in the MRB to address this problem (Rabalais & Turner, 2019).

Further contributing to environmental issues is the energy consumption and pollution that can also be attributed to fertilizers in some way. Ammonium fertilizer production is an energy-intensive process and phosphate mining involves many damaging practices.

Although methods have been studied to reduce the energy requirements of the Haber-Bosch process, it accounts for 1%-2% of energy consumption and carbon dioxide (CO_2) emissions globally, making ammonia the chemical with the highest energy consumption (Kyriakou et al., 2020). Among the three most common crops in the U.S., corn, soybeans, and wheat, fertilizers accounted for roughly 20-40% of the total energy inputs used to grow them with nitrogen fertilizers requiring almost 4.5 times more energy than phosphate and more than 5.5 times more energy than potassium oxide (Amenumey & Capel, 2014).

Once applied, nitrogen fertilizers can leak from the system through nitrification and denitrification as nitrous oxide, a greenhouse gas that traps heat three hundred times more effectively than carbon dioxide, or through volatilization as ammonia. 75% of the nitrous oxide emissions come from agricultural systems(Cavigelli et al., 2012), and the United States alone is estimated to contribute 13% of global agricultural nitrous oxide emissions (West et al., 2014).

An estimated 40-70% of nitrogen that is applied is lost, with volaltilization accounting for 10-14% of these losses (Li et al., 2022). Deposition of nitrogen from the atmosphere has similar effects to intentional fertilization, such as acidification and eutrophication, but can have widespread effects in various ecosystems (Galloway et al., 2003). Even in non-agricultural terrestrial ecosystems, nitrogen can cause long-lasting shifts in species composition that spans the microbial level to plant assemblages (Bowman et al., 2018), which could feasibly influence animal populations as well. Limiting any excess production of nitrogen as well as determining the best fertilizer application practices to reduce all losses is another important part of limiting the detrimental effects of fertilizer usage along with mitigating nutrient losses to water systems.

Economic Impacts

The consequences of nutrient pollution from agriculture and the efforts to mitigate them come with severe economic costs. There is a financial incentive for farmers to purchase as little fertilizer as needed, but the yield penalty of not applying enough fertilizer can be enough to reduce profits and applying too much fertilizer is often more economic than applying too little (Sadeghpour et al., 2017). When this leads to pollution, the costs become societal and difficult to estimate with substantial variations depending on what factors are being accounted for. A study by Dodds et al. in 2009 estimated that $2.2 billion is lost annually due to impacts on recreational industries related to polluted waters and property values of waterfront real estate, the protection aquatic ecosystem diversity and endangered species, and the treatment of drinking water in U.S. freshwaters. More recently, Del Rossi et al. (2023) highlight the need to address additional concerns, such as treatment for associated health problems, reduction of greenhouse gas emissions, and loss of income to fisheries, and more extreme estimates of reactive nitrogen damages alone in the U.S. ranged from $81-441 billion annually in the early 2000s (Sobota et al., 2015). Implementing practices to mitigate nutrient losses can have considerable monetary benefits; one study estimates than in the U.S., an investment of $900 million in a variety of practices could produce $50 billion in benefits that include improved yields and avoiding damages to human health and the environment, and globally, a $19 billion investment could produce $476 billion in benefits (Gu et al., 2023). Along with the intrinsic value of healthy populations and ecosystems, this highlights the need to improve fertilizer efficiency and prevent excess nutrients losses before they can cause damages.

MULTICROPPING PRACTICES

DEFINITIONS

Multicropping, growing more than one crop in the same area during the same year, can refer to several different agricultural practices, but cover cropping and double cropping will be the focus of this thesis. Both involve growing a second crop in a field following a cash crop, but a double cropped field is harvested twice and thereby considered a form of agricultural intensification while a cover cropped field is only harvested once (Borchers et al., 2014), unless the cover crop is harvested for hay or silage rather than grain or seed (Wallander et al., 2021). Cover cropping is a common method of conservation for its reported benefits of preventing soil erosion and nutrient leaching and potential for retaining soil moisture given that appropriate management practices are used (Kaspar & Singer, 2011).

Double cropping, along with potentially reducing the amount of land use change needed to keep up with growing food demands (Gammans et al., 2019), also keeps cover on what would otherwise be bare soil. This could provide similar physical benefits to cover cropping, but may increase pollution from fertilizers, herbicides, pesticides, and other chemicals used to maintain crop yields (Borchers et al., 2014). With other conservation practices, such as reduced or split fertilizer applications, conservation tillage or no-till, and proper crop selection, negative impacts may be reduced while maximizing the benefits. Double cropping may also be appealing to farmers not already using cover crops due to the potential income from a second crop, providing an economic incentive to convert from bare fallow practices.

ADOPTION IN THE US

Cover cropping is a term that many in the United States have heard but the term double cropping is not as familiar, reflecting a trend in both the adoption and discussion of these practices. Globally, multicropping practices were used on about 12% of agricultural land between 1998 and 2002, and much of this land occurred in tropical or subtropical climates, regions with low to lower middle incomes, or both (Waha et al., 2020). In the United States, monoculture systems became especially prevalent in the 20th century through technological as well as legislative means that focused more on producing the highest yields of one high-value crop per year (Kelly, 2019). Cover cropping and double cropping in temperate climates have become more common in scientific literature as focus on sustainable agriculture increases, but implementation is often still limited. Between 1999 and 2012, cover cropping constituted only 1-2% of cropland (6-7.7 million acres) and double cropping made up 2-3% (6-11 million acres), although double cropping rates are highly variable on an annual basis and seem to follow trends in commodity prices (Borchers et al., 2014). Rates of cover cropping have grown 50% as of 2017 with 15.4 million acres being reported (Wallander et al., 2021), but the USDA has not updated reports on double cropping. Despite the increase in adoption rates for cover cropping, overall adoption is still low, reflecting the problems that remain with enacting multicropping on a larger scale.

ADOPTION LIMITATIONS

While interest in double and cover cropping has grown, there are still many barriers to overcome before they can become common practices. Farmers may be hesitant to implement these practices due to uncertainties involving logistics of these systems and the short- and long-term costs and benefits, as demonstrated by a focus group about cover cropping led by Roesch-McNally et al. (2017). While the interactions of these agricultural systems and environmental conditions may never be fully understood, especially as climate change adds even more complexities, more research will improve the advice given to maximize the environmental benefits as well as profits and yields. As is often the case, concerns with the financial aspect of multi cropping must always come into decision making. According to the SARE (2020) national cover crop survey, in which farmers self-report data, farmers that did not use cover crops reported a lack of economic return and yield reduction in cash crops as two of the top three major concerns about adopting the practice. Those that did adopt the practice reported that the per-acre range of cover cropping costs was \$15-\$78 with an average cost of \$37. Despite potentially significant upfront costs and profit losses in the first year, farmers began seeing savings and profit gains over time. Some of these savings on inputs like fertilizer, pesticides, and fuels could be substantial. Some farmers have also reported higher incomes from circumstances such as having extra yields after a drought year where cover cropped land was more resilient (Myers et al., 2019). Even then, many farmers do not want to or cannot wait for these savings or payouts, making secondary income from double cropping a potentially more appealing way to keep groundcover all year, especially if insurance for a second yearly crop becomes more common through legislation like the Double Cropping Initiative (USDA, 2022). Establishing more reliable markets for winter crops like wheat and determining whether annual profits justify the practice can also help farmers make more informed decisions (Franch et al., 2015).

CROP CONSIDERATIONS

As with any conservation practice, multicropping must be implemented correctly to bring about the desired outcome. The physiological properties of the plant chosen will determine its effectiveness for desired outcomes, so aspects like root structure, water and nutrient uptake, conditional tolerances, and post-harvest residues should align with management and economic goals. Cover crops fall into two general categories- legumes, which fix nitrogen that the following cash crops can utilize and have a low C:N ratio that will reduce nitrogen immobilization as residues decompose, and nonlegumes, which will scavenge nutrients that may otherwise be lost. Within these categories, various plants can be chosen to meet additional goals. For erosion control, a plant that is closer to the ground and covers a substantial percentage of the soil should be chosen. To increase the amount of organic matter in the soil or create a lasting mulch, grasses work well due to the higher carbon content. Deep-rooting plants can improve subsurface compaction and plants with more lateral roots can improve surface compaction (Sarrantonio, 2007). Resources like the Cover Crop Decision Tool from the Midwest Cover Crop Council can help simplify the selection process by providing regional information for common cover crops and allows users to select management goals. Some of these crops can be used as double crops, but double crop selections tend to reflect commodity prices and regional environmental conditions and attitudes (Borchers et al., 2014).

Cereal rye is often used as a cover or double crop because it has many qualities that make it beneficial for that purpose. These properties include being more cold resistant than most other crops, allowing it to grow continuously through the winter in temperate climates. It has robust root systems that can improve the tilth of the soil and helps it tolerate a variety of soil conditions. The production of allelopathic compounds aid in weed suppression (Grubinger, 2021) but may also have a negative impact on cash crop yields, especially in the germination stage, although these effects are still not well understood (Koehler-Cole et al., 2020). Cereal rye residues have a high C:N ratio that can cause nitrogen immobilization that restricts the access of nutrients to subsequent cash crops, but carbon-rich materials with a slow decomposition rate can release nutrients longer into the growing season than a legume that decomposes quickly, and these persistent materials provide other benefits to the soil (Sievers & Cook, 2018).

Winter wheat is another common option for winter ground cover, and while cereal rye is often preferred over winter wheat as a cover crop (Wallander et al., 2021), winter wheat is often preferred as a double crop (Borchers et al., 2014). It is also hardy enough to grow over the winter season and can also improve soil tilth, but its finer root system makes it less tolerant of poor conditions than cereal rye (SARE, 2007). Winter wheat is also allelopathic, giving it some of the same benefits (Grubinger, 2021) and drawbacks as cereal rye (Koehler-Cole et al., 2020), but with less crop residues than cereal rye, farmers may find it easier to harvest and plant into afterwards. For producers with livestock, both options are viable as a cover crop with the intention of foraging. Cereal rye is better for poor conditions and earlier grazing in the spring but will reach maturity faster while winter wheat will have a higher quality later in the spring but may not support as many animals if it goes dormant due to cold temperatures (Anderson, 2008).

As a second cash crop, winter wheat is an economically sound choice compared to others. Winter wheat tends to have a higher value per bushel than cereal rye and higher average yields per acre, with winter wheat averaging $8.70 per bushel and 47 bushels per acre, or $408.9 per acre, and cereal rye averaging $7.50 per bushel and 36.1 bushels per acre, or $270.75 per acre in

2022 (National Agricultural Statistics Service [NASS], 2023a; NASS, 2023b). Winter wheat also has higher production in the U.S. overall, over 1 billion bushels of winter wheat compared to over 12 million bushels of cereal rye and has reported production in 35 states compared to the 14 states that reported production of cereal rye (NASS, 2023a), implying that the market for winter wheat is more widely available than for cereal rye and others.

COMPARING MULTICROPPING PRACTICES

NUTRIENT LEACHING

One aspect of cover cropping that makes it more favorable than double cropping as a sustainable practice is the reduction of nutrient loading compared to double cropping where fertilizers are used to maintain yields and may negate the positive effects of having winter ground cover. As a water-soluble ion, nitrate leaching can be challenging to control. Besides creating wetlands or riparian buffers or converting farmland to perennial vegetation, which may not be attractive options to farmers, cover crops have been identified by the NLRS (2015) as the best in-field practice for nitrate reduction, estimated to produce a 30% reduction in nitrate and phosphorus per acre on both tile-drained and non-tiled acres. This is likely a conservative estimate, however; a meta-analysis of 69 international studies by Tonitto et al. (2006) reported a reduction in nitrate leaching that averaged 70% with non-leguminous cover crops as well as 40% with leguminous cover crops, and another reported an average reduction of 68% for all species (Nouri et al., 2022). In studies from the US, the percentage of nitrate leaching reduced by cereal grain cover crops ranged from 13-94% (Kladivko et al., 2014), and simulations estimate a 42.5% nitrate reduction in tile-drained Midwestern fields with the use of cereal rye (Malone et al., 2014).

Phosphorus leaching in the form of dissolved reactive phosphorus (DRP) can also contribute to excess nutrient contamination but is difficult to quantify on a large scale and not considered to be a significant source of phosphorus loss compared to what is lost from surface-level soil erosion. Because of this, the Illinois Nutrient Loss Reduction Strategy (NLRS) does not address phosphorus leaching and focuses instead on total phosphorus reductions from soil erosion, but it does note that DRP continues to affect surface waters as erosion is reduced and lists agricultural leachate and runoff as one potential source (Illinois Nutrient Loss Reduction Strategy, 2015). DRP leaching may not be a significant contributor to excess nutrients in all surface waters (Sharma et al., 2017) but is influenced by soil conditions (Djodjic et al., 2004; Dymond et al., 2013) so amounts may be underestimated in some regions. Phosphorus losses in cover cropped systems are less studied than nitrogen losses and the data and conclusions drawn are less consistent. This is demonstrated in a paper by Aronsson et al. (2016) where researchers examined six experimental sites in Sweden with data on phosphorus losses in cover cropping systems, compared to eleven with data on nitrogen losses across four Nordic countries. Their study showed that phosphorus leaching ranged from reductions of 43% to increases of 86%, potentially offsetting the benefit from reducing particulate P runoff from erosion control and linked increased phosphorus release to freeze-thaw cycles. Another study showed an increase in DRP leaching with cover crops in three of four years along with a 40% reduction of total P one year, an increase of 56% one year, and no effect in the other two years, which was linked to the effects of sediment loss. Fertilizer management was shown to be the more important method of reducing phosphorus losses compared to cover crops (Carver et al., 2022).

Comparative studies that include both double crops and either bare fallow or cover crops are limited, highlighting the need for research on this topic. At least one study reported a 25-34%

reduction in potential nitrogen leaching in a double cropping system with winter triticale followed by corn, sorghum-sudangrass, or sunn hemp, and an 83% and 41% increase in nitrogen and phosphorus uptake, respectively in two of these systems, but these two systems also had an increased potential for leaching during the summer, so overall impacts are still uncertain (Heggenstaller et al., 2008). Leaching was not measured directly, and potential leaching was also compared to a single corn cropping system rather than a cover cropping system, so it is not possible to draw comparisons between the leaching potentials of multi cropping systems. Brown (2006) reported a 29.8-42.2% increase in total phosphorus uptake in corn systems double-cropped with barley, wheat, or triticale compared to corn alone, but did not assess losses such as runoff or leaching. These studies demonstrate the potential for reductions in nutrient leaching, but no significant conclusions can be drawn.

PHYSICAL SOIL PROPERTIES

One way that cover cropping and double cropping function in the same manner is regarding their impacts on physical soil properties. Crop physiology will influence these properties, as previously stated, as well as the management practices used. Tillage practices, for example, also greatly influence physical properties of soil, and farmers who use cover crops are more likely to use conservation tillage or no-till practices (SARE, 2020). Cover cropping has many reported benefits for soil health. Aboveground and root biomass inputs will contribute to soil organic carbon over time. Erosion can be reduced by providing physical cover to the soil, providing roughness to slow down runoff, and improving water infiltration. Soil tilth is improved when cover crop roots penetrate compact soil layers and create biopores as well as increase aggregate stability. These improvements to soil environments along with more diversity in organic matter inputs can also increase the diversity and populations of biological communities

(Blanco-Canqui et al., 2015; Haruna et al., 2020; Sharma et al., 2018). Cover crops can reduce evaporation from solar radiation and wind but can also increase transpiration, making the effects on soil moisture more variable than other factors (Kaspar & Singer, 2011). Similar effects have been reported in double cropping systems, especially when used in conjunction with conservation tillage, but the number of double cropping studies are limited in number as well as length, so the long-term effects are not definitive (Egbedi, 2022; Liesch et al., 2011).

Crop Yields

Though potential yield losses have dissuaded some farmers from using multi-cropping practices, research has shown that this concern may be unfounded. Individual studies, which are often short term and span only one crop rotation over two years, tend to report a variety of findings. For example, Ruffo et al. (2004) reported no significant differences in soybean yields following a cereal rye cover crop, Chu et al. (2017) reported a significant increase in soybean yields when using a mix of five cover crop species, Adeyemi (2020) reported a decrease in corn yields following wheat cover crops, and many other papers on the topic follow the same trend of inconsistent conclusions. Recognizing this, Tonitto et al. (2006) did a meta-analysis on cash crop yields following cover crops with 31 studies each on leguminous and non-leguminous cover crops with similar environmental conditions, finding no significant changes from bare fallow systems overall and a meta-analysis by Marcillo & Miguez (2017) of over 200 studies showed no significant corn yield penalties following grass cover crops and a positive response corn yield response following leguminous cover crops, especially in no till systems, when nitrogen fertilizer rates are less than 200 kg ha^{-1}, with a mixture cover crops, and with later termination dates. Many variables, such as seasonal weather or soil conditions, may contribute to how cash crops are impacted by cover crops, but cover crops alone are not a significant factor overall.

Double cropping, which is more focused on total yields from both crops, has shown promising results for crop yields. A study with 132 farms in eleven zones of the Argentine Pampas reporting crop yields for corn, soybean, and wheat-soybean double crops showed that while corn had the highest grain yields, wheat-soybean rotations had higher yields than soybean alone, especially in marginal areas (Andrade & Satorre, 2015). When looking at soybean grain yields and profits, there will be a penalty from double cropping with wheat, but combined grain yields were higher than in monocultures of soybeans and profits were shown to be not significantly lower (Shrestha et al., 2021), or equal to or greater than monoculture soybeans alone (Kyei-Boahen & Zhang, 2006). Corn yields and total biomass were shown to be greater with leguminous double crops compared to monoculture corn (Fernández-Ortega et al., 2023) and total biomass was shown to be greater in corn systems with triticale double crops despite greater maximum leaf area index and growth rates in sole corn (Heggenstaller et al., 2008).

SUSTAINABLE FERTILIZER MANAGEMENT

The 4Rs of fertilizer management- right rate, right source, right placement, and right timing- are used as guidelines to achieve sustainable agriculture, but these practices can always be improved upon. Nitrogen use efficiency (NUE) is estimated to be 35% or less and phosphorus use efficiency (PUE) is estimated to be 20% or less and though nutrient use will never be 100% efficient, there are ways to increase it (Umar et al., 2020). Nutrient management practices are the most effective way to increase NUE in croplands and finding the correct rate and timing for fertilizer applications can increase NUE by 11% and 7%, respectively, and by 39% and 24%, respectively, compared to unfertilized controls (You, et al., 2023).

RATE DETERMINATION

Minimizing the amount of fertilizer being applied beyond what is needed for optimal crop yields is the first step to reducing nutrient losses. The Maximum Return to Nitrogen (MRTN) tool provides state or regional estimates of rates at which nitrogen fertilizers will maximize economic returns from corn yields without overapplying but is limited to corn rotations in the Midwest. No such tools are available for winter wheat fertilizer recommendations due to the lack of widespread research on this crop, leading to uncertainty regarding the economic optimum nitrogen rate in winter wheat.

SPLIT FERTILIZER APPLICATION

Split fertilizer application provides smaller but more frequent fertilizer applications to crops. This is done to improve nutrient use efficiency, especially with highly mobile nitrogen, by limiting the amount being applied, which may be leached, offgassed, run off, or made unavailable before it can be used, but reapplying often enough to accommodate crop nutrient needs. In treatments with only two applications, such as preplant and sidedress that is typical in corn, higher amounts of rainfall close to fertilizer applications can reduce grain yields and NUE (Adeyemi et al., 2020; Lu et al., 2021). At least two fertilizer applications, in fall and spring, are recommended to maximize winter wheat yields, but two spring applications can improve yields and NUE even further (Alley et al., 2019).

DELAYED FERTILIZER APPLICATION

Delayed fertilizer application uses knowledge of a crop’s nutrient uptake patterns to apply fertilizer when it is most needed. By applying fertilizer when nutrient needs increase rather than at or before planting when nutritional needs are lower, a plant can utilize more of what is applied, and this is often combined with split applications to improve efficiency even more. For winter wheat, an initial application of fertilizer is recommended to ensure establishment before winter dormancy, but nitrogen is often only required in small amounts or may not be required at all if the soil is already high in nitrogen (Alley et al., 2019). Although studies have shown that delaying fertilization in winter wheat does not always cause a yield penalty, environmental factors such as precipitation and soil nitrogen levels can be influential on yields (Boman et al., 1995; Efretuei et al., 2016).

CHAPTER 2

METHODS

STUDY SITE

This study was conducted at the Agronomy Research Center (ARC) in Carbondale, IL, a property owned by Southern Illinois University Carbondale (SIUC) (Figure 2.1). Field 18D is 0.7 hectares and plots are 9.144 m by 9.144 m with 9.144 m wide rows separating blocks of sampled plots. The soil at the study site consists of Stoy silt loam, a fine-silty, mixed, superactive, mesic Fragiaquic Hapludalf classified as prime farmland. Soils have a plowed A horizon of 0-33 cm, a 30.5-91.4 cm depth to water table, and a 101.6-119.4 cm depth to restrictive fragipan and have a 0-5% slope, a somewhat poorly drained drainage class and high runoff class.

Based on 30-year averages from 1991-2020, mean annual air temperature for Carbondale, IL is 13.58°C and cumulative precipitation is 1117.85 mm. During the May-October growing season, mean air temperature is 21.2°C and cumulative precipitation is 562.4 mm and during the November-April winter/spring season, mean air temperature is 6°C and cumulative precipitation is 555.5 mm. (Figure 2.2). All weather data was taken from a University of Illinois weather station installed at the ARC (Water and Atmospheric Resources Monitoring Program [WARM], 2019).

Figure 2.1. Aerial photo of SIUC's ARC property with field 18D highlighted and coded with the Web Soil Survey map unit symbols (USDA, 2024).

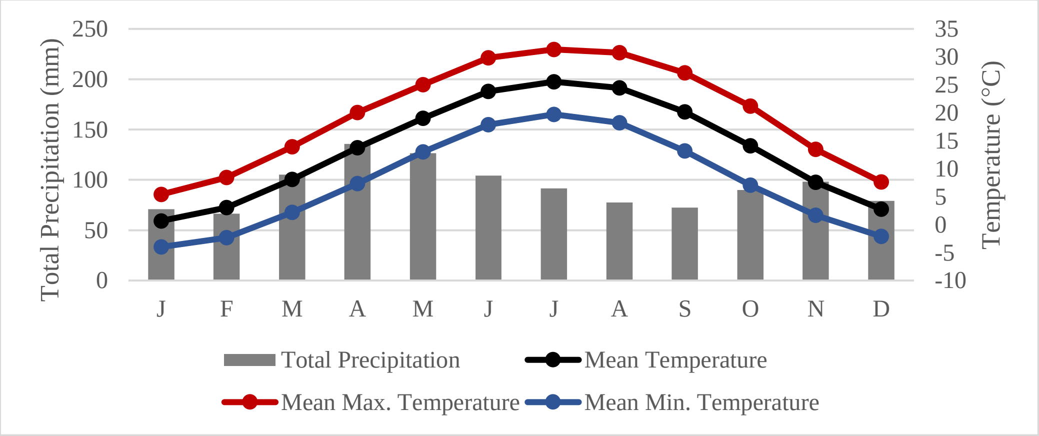

Figure 2.2. Total precipitation, mean temperature, mean maximum temperature, and mean minimum temperature based on 30-year averages from Water and Atmospheric Resources Monitoring Program weather station.

SITE PREPARATION

Site preparation for the experiment began in October 2021 (Table 2.1). Pan lysimeters, also called zero-tension lysimeters, were chosen because they can estimate in-field nutrient loading rates for every rain event significant enough to cause leaching by collecting leachate that freely drains from soils during and following rain events to be analyzed for nutrient concentrations (Zhu et al., 2002). A pan lysimeter was installed at each plot between October 20-22, 2021, following corn harvest. These lysimeters have a collection pan made from dense, non-reactive plastic filled with fine silica sand for drainage and were installed by excavating a pit near the center of each plot. Visual identification of lighter textured soils, indicating a transition to the first silt clay loam E horizon, was used to determine collection pan depths, which ranged from 17.8 and 35.1 cm (Figure 2.3). Lateral holes were dug underneath the undisturbed A soil horizon, which was used due to the restrictive silt clay loam horizons at lower depths that prevent further downward drainage but can contribute to subsurface runoff from the field, and the space around the pan was backfilled with the removed soil (Figure 2.4). Collection pans have a 0.086 m^2 surface area and drain through plastic tubes into dense, non-reactive plastic reservoirs with a volume of 27.75 L. Reservoirs have a plastic tube extending from the bottom of the pan to above the soil surface to pump water through and a plastic tube extending from the top of the reservoir to above the soil surface to prevent negative air pressure when removing water (Figure 2.5). Pits were then backfilled with the removed soil while replacing as much of the topsoil on the surface as possible and allowed to settle before water sampling began.

Suction cup lysimeters, referred to in this paper as tension lysimeters, were chosen because they can estimate plant available nutrients by using negative pressure to draw in soil solution through a porous cup (Singh et al., 2017), but less negative pressure than the permanent wilting point of plants. Tension lysimeters (Figure 2.6) were installed at each plot on December 9, 2021 by digging a hole roughly 30.5 cm deep, filling the area around the ceramic cup with a silica flour slurry, and backfilling the rest of the hole with native soil (Figure 2.7).

Table 2.1. Dates and descriptions of field work completed over the course of the study, including remarks when applicable.

	Date	Field Work Completed	Remarks
2021	10/20/21-10/22/21	Pan lysimeters installed	
	10/26/21	Winter wheat and cereal rye planted	Winter wheat: AgriMaxx 495, 140 kg ha^{-1} Cereal rye: SoilFirst, 87 kg ha^{-1}
	11/18/21	Fall fertilizer applied	DAP: 168 kg ha^{-1}, 30 kg ha^{-1} of N (high treatment)
	12/09/21	Tension cup lysimeters installed	
2022	2/14/23	First samples taken	
	3/16/22	Tillering fertilizer applied	DAP: 168 kg ha^{-1}, 30 kg N ha^{-1} (medium and low treatment) UAN: 79 kg N ha^{-1} (high and medium treatment), 45 kg N ha^{-1} (low treatment)
	5/3/22	Jointing fertilizer applied	UAN: 79 kg N ha^{-1} (high and medium treatment), 45 kg N ha^{-1} (low treatment)
	5/11/22	Burndown of no cover and cereal rye control plots	RoundUp PowerMax mix
	5/18/22	Soybeans planted in control plots	Asgrow 47xF0, 395,000 ha^{-1}, Kinze 4 row planter
	6/22/22	Wheat harvested	
	6/22/22	Late soybeans planted	Asgrow 47xF0, 395,000 ha^{-1}, Kinze 4 row planter
	6/24/24	Pre emergence weed application	2.5% AMS, 0.4 L ha^{-1} RoundUp, 0.4 L ha^{-1} Liberty, and 0.8 pt ha^{-1} Prefix
	7/19/22	Post emergence weed application	0.4 L ha^{-1} RoundUp and 0.4 L ha^{-1} Liberty
	10/04/22-10/13/22	Lysimeter tubes buried	
	10/24/22	Soybeans harvested	
	10/24/22	Cereal rye planted	SoilFirst, 87 kg ha^{-1}
	10/27/22-10/28/22	Lysimeter tubes unburied	
2023	3/27/23	Drone imagery taken for field	
	3/27/23	GPS points taken for lysimeter locations	
	4/25/23	Burndown of all plots	RoundUp PowerMax mix
	5/15/23	Pan lysimeter 101 unburied and checked for leaks	
	5/15/23	Lysimeter tubes buried	
	5/18/23	Corn planted	84,000 ha^{-1}
	5/18/23	Fertilizer applied	45 kg N ha^{-1}
	5/19/23	Lysimeter tubes unburied	

	6/22/23	Sidedress fertilizer applied	UAN: 179 kg N ha^{-1}
	10/13/23	Lysimeter tubes buried	
	10/16/23	Corn harvest	
	10/18/23	Wheat and cereal rye planted	Winter wheat: AgriMazz 495, 140 kg ha^{-1} Cereal rye: SoilFirst, 87 kg ha^{-1}
	10/19/23	Fall fertilizer applied	DAP: 168 kg ha^{-1}, 30 kg N ha^{-1} (high treatment)
	10/20/23	Lysimeter tubes unburied	

Figure 2.3. Visual indication of A soil horizon and first clay silt loam E horizon used to determine collection pan placement.

Fig. 2.4. Pan lysimeter collection plate placement in a research plot (left) and after being backfilled (right).

Fig. 2.5. Complete pan lysimeter installation before backfilling with soil.

Figure 2.6. Example of the tension lysimeters used.

Figure 2.7. Example of tension lysimeter installation with silica flour slurry.

EXPERIMENTAL DESIGN

This study was a randomized complete block design with four blocks and eight treatments. Two treatment factors were used; crop rotation had two treatment levels and intensity of nitrogen fertilizer management had four treatment levels (listed below). No fertilizer treatments were not planted with winter wheat and represented corn-soybean rotations with either no cover (bare fallow) or cereal rye cover crops (cover crop) between cash crops. Each of these eight treatments (listed below) were randomly assigned to one of eight plots in a block (Figure 2.8).

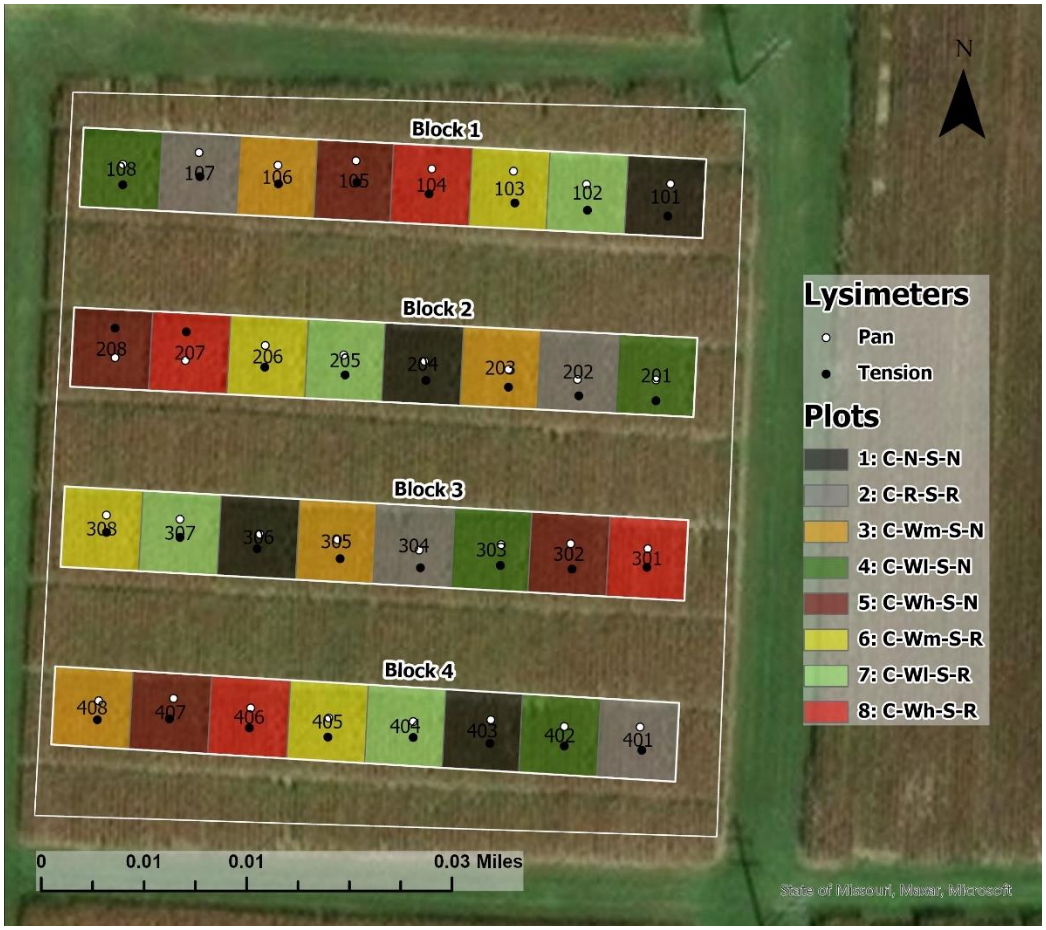

Figure 2.8. Field 18D map with block arrangement and treatments assigned to plots.

TREATMENTS

Crop rotation treatment factor:

- BF: corn-winter wheat-late soybean-no cover (treatments 1, 3, 4, and 5)
- CC: corn-winter wheat-late soybean-cereal rye cover crop (treatments 2, 6, 7, and 8)

Fertilizer management for winter wheat treatment factor:

- H: high input (treatments 5 and 8), 168 kg ha^{-1} of DAP in the fall, 79 kg N ha^{-1} of 32% UAN at tillering, and 79 kg N ha^{-1} of 32% UAN at jointing (based on NREC grower recommendations)
- M: medium input (treatments 3 and 6), 168 kg ha^{-1} of DAP in the spring, 79 kg N ha^{-1} of 32% UAN at tillering, and 79 kg N ha^{-1} of 32% UAN at jointing
- L: low input (treatments 4 and 7), 168 kg ha^{-1} of DAP in the spring, 45 kg N ha^{-1} of 32% UAN at tillering, and 45 kg N ha^{-1} of 32% UAN at jointing
- N: no input (treatments 1 and 2), no fertilizer

All treatments:

1. Corn-no cover-soybean-no cover with no winter fertilizer (C-N-S-N, control)
2. Corn-cereal rye cover crop-soybean-cereal rye cover crop with no winter fertilizer (C-R-S-R, recommended nitrate-N reduction control)
3. Corn-wheat (medium input)-soybean-no cover (C-Wm-S-N)
4. Corn-wheat (low input)-soybean-no cover (C-Wl-S-N)
5. Corn-wheat (high input)-soybean-no cover (C-Wh-S-N)
6. Corn-wheat (medium input)-soybean-cereal rye cover crop (C-Wm-S-R)
7. Corn-wheat (low input)-soybean-cereal rye cover crop (C-Wl-S-R)
8. Corn-wheat (high input)-soybean-cereal rye cover crop (C-Wh-S-R)

MANAGEMENT

Winter wheat (AgriMaxx 495) was planted in winter wheat treatment plots on October 26, 2021, following the 2021 corn harvest and October 18, 2023. The seeding rate was 140 kg ha^{-1} of seed with fertilizer rates based on fertilizer management intensity treatment factor (listed above) and seeds were treated with fungicides and insecticides. Cereal rye (SoilFirst) was planted in cereal rye control treatment plots at 85 kg ha^{-1} of seed with a small grain drill on the same dates. Control treatment plots were burned down on May 11, 2022, and winter wheat was harvested on June 22, 2022, but the 2023-2024 growing season was still in progress at the time of this study.

Normal duration soybeans (Asgrow 47xF0) were planted in control treatment plots on May 18, 2022, and late soybeans were planted in winter wheat treatment plots on June 22, 2022. The seeding rate was 395,000 plants ha^{-1} using a Kinze 4 row planter with a row spacing of 76 cm. Soybeans were harvested on October 24, 2022.

Cereal rye was also planted in cereal rye cover crop plots with the above specifications on October 24, 2022. All plots were burned down with RoundUp PowerMax mix on April 25, 2023.

Corn (DKC 64-34) was planted in May 2021 proceeding the site preparation and sampling for the 2023 corn season began on May 18, 2023. The planting rate for corn was 84,000 plants ha^{-1} with a row spacing of 76 cm and the fertilizer rate was 45 kg N ha^{-1} of 32% urea ammonium nitrate (UAN) at planting (20% of total application) and 180 kg N ha^{-1} at sidedress (80% of total application), the MRTN agronomic rate of the region. Corn was harvested on October 16, 2021 with an 8-XP Plot Combine (Kincaid, Haven, KS).

FIELD METHODS

PAN LYSIMETER SAMPLING

Pan lysimeters were sampled following rain events of 12.7 mm or greater or weekly after multiple rain events with at least 12.7 mm of accumulation, allowing at least 24 hours after rain events to allow infiltration into and percolation through soil. Soil solution was pumped from the collection reservoir into a graduated measuring device. A sample was taken for laboratory analysis if volume was 75 mL or greater, and total volume was recorded. Samples were filtered through 45 µm filters after being agitated through shaking (Sartorius Lab Instruments GmbH&Co.KG, Goettingen, Germany) and frozen until laboratory analysis. Soil disturbance from the installation process can cause increases in nitrogen mineralization rates, so the first four months of samples were excluded from analysis. Collection dates for included samples began 03/08/22 and ended 01/26/24.

Figure 2.9. Pan lysimeter sampling equipment.

TENSION LYSIMETER SAMPLING

At least 72 hours before collection in the first week of the month, a pressure-vacuum hand pump was used to create a vacuum of at least 50 centibars inside of tension lysimeters. A pressure-vacuum hand pump was used to empty soil solution into 250 mL plastic Nalgene sample bottles. Samples were filtered through 45 µm filters after being agitated through shaking (Sartorius Lab Instruments GmbH&Co.KG, Goettingen, Germany) and frozen until laboratory analysis. Soil disturbance from the installation process can cause increases in nitrogen mineralization rates, so the first four months of samples were excluded from analysis. Collection dates for included samples began 03/08/22 and ended 03/04/24.

Figure 2.10. Tension lysimeter sampling equipment.

CROP SAMPLING

Wheat and soybean samples were harvested from the ground surface at maturity using grass shears prior to combine harvest. Three 0.2 m^2 frames in each plot's interior were used for sample collection, a total area of 0.6 m^2. Grain yields were then dried and weighed. This procedure was also used to collect wheat and soybean plant tissue samples, which were then dried at 60°C until a constant dry weight was reached, ground to a 0.6 mm particle size, and analyzed for total nitrogen at Water Laboratories, Inc. Corn was harvested with an 8-XP Plot Combine (Kincaid, Haven, KS) at maturity and dry weights of grain yields were recorded. Nitrogen removal in corn was estimated using the regression of grain yield (Mg DW ha^{-1}) multiplied by 11.5 reported by Tenorio et al. (2018).

LABORATORY ANALYSIS

Water samples were thawed at room temperature overnight before laboratory analysis. To analyze nitrate-N, thawed water samples were first agitated. Ion chromatography (Thermo Scientific Dionex Aquion Ion Chromatography System, Thermo Finnigan LLC CA, USA) was used to analyze nitrate and nitrate-N was determined using molecular weights.

A spectrophotometer (Perkin Elmer Lambda 25 UV/Vis Spectrometer, PerkinElmer, Inc. CT, USA) was used to analyze concentrations of ammonium-N and DRP in prepared samples following the creation of a calibration curve using standards with known concentrations. Deionized water was used to flush the sipper tube between standards and samples. Water samples were diluted with deionized water as needed if sample volume was limited or concentrations exceeded calibration, and concentrations were adjusted accordingly prior to statistical analysis. Loading rates per rain event for nitrate-N, ammonium-N, and DRP in pan samples were calculated using the concentrations, collection pan area, and total volume collected (equations are reported in appendix A).

A primary ammonium stock was created with 3.819 g of anhydrous ammonium chloride (NH_4CL) in 1 L of deionized water, and the secondary ammonium stock was made the day of analysis from 0.5% primary ammonium stock and 99.5% deionized water. This secondary ammonium stock was used to prepare 0%, 4%, 10%, 16%, and 20% standard solutions. Samples and standards were prepared by measuring 25 mL of the water sample or standard solution into test tubes along with, in order under a fume hood, 1 mL of phenol solution, made from 8.9% phenol and 91.1% ethyl alcohol, 1 mL of sodium nitroprusside, made from 0.5 g of sodium nitroprusside dissolved into 100 mL of deionized water, and 2.5 mL of oxidizing solution, made from 20% sodium hypochlorite and 80% alkaline citrate. Test tubes were capped and inverted twice to evenly distribute the solution and the color developed in a dark area for at least an hour.

A primary phosphorus stock was made within a month of analysis from 0.219 g potassium phosphate monobasic anhydrous (KH_2PO_4) dissolved into 1 L of deionized water, and secondary stock was made the day of analysis from 5% primary stock and 95% deionized water. This secondary stock was used to make 0%, 2%, 4%, 20%, and 40% standard solutions. Samples and standards were prepared by measuring 50 mL of the water sample or standard solution. 0.5 g of phenolphthalein was dissolved into 50 mL of ethyl alcohol and a drop was added to samples to test pH. 5 N sulfuric acid was made by mixing 140 mL of sulfuric acid (H_2SO_4) in deionized water and then filling with more deionized water to a total volume of 1 L in an ice bath under a fume hood, which was added a drop at a time to reduce pH of water samples if needed. A combined reagent was made within 4 hours of analysis by adding, in order, 50% 5N sulfuric acid, 5% potassium antimonyl tartrate solution, made from 1.3715 g of antimonyl potassium tartrate ($C_8H_4K_2O_{12}Sb_2$) dissolved in 500 mL of deionized water, 15% ammonium molybdate solution, made by dissolving 20 g ammonium molybdate ($(NH_4)_2MoO_4$) into 500 mL of deionized water, and 30% ascorbic acid solution, made by dissolving 4.4 g ascorbic acid ($C_6H_8O_6$) into 250 mL of deionized water. 8 mL of combined reagent was added to standards and water samples, the color developed for at least 10 minutes, and analysis was performed within 30 minutes.

STATISTICAL ANALYSIS

All data were analyzed using JMP Pro 17.2.0 (SAS Institute Inc., Cary, NC, 2023).

WATER DATA

Samples with nutrient concentrations too low for detection by laboratory equipment were excluded from statistical analysis. Data were analyzed for a normal distribution using Shapiro-Wilk and Anderson-Darling goodness-of-fit tests and transformed using a Log10 function if needed but means and other values are reported in the original scale. A mixed model with repeated measures was used for data analysis. Crop rotation and fertilizer management intensity hereby referred to as ‘rotation’ and ‘fertilizer,’ were used as fixed factorial treatments to test for treatment effects and interaction effects and block was used as a random effect. For systemic leaching and plant available nutrients, the season of sampling, hereby referred to as ‘season,’ was also used as a factor. An AR(1) repeated covariance structure was used with the plot number used as the subjects and the number of days since the beginning of the time interval used as the repeated measurement. With the results from this test, multiple comparisons were run to determine any significant differences within treatment factors using a Tukey’s HSD test for the fertilizer treatment and interaction effects if significance was detected at alpha =0.05.

CROP DATA

Crop yields were converted to Mg DW ha^{-1} using harvest weight and moisture content. Partial nitrogen balances were calculated by subtracting nitrogen removal from total nitrogen application in seasons when fertilizer was used. Cumulative nitrogen leaching and crop yields were used to calculate yield-based nitrogen losses in kg Mg^{-1} in seasons when fertilizer was applied. (equations are reported in appendix A). Data were analyzed for a normal distribution using Shapiro-Wilk and Anderson-Darling goodness-of-fit tests. Crop yield, nitrogen uptake, and partial nitrogen balances were transformed using a Log10 function if needed and yield-based nitrogen leaching data was transformed using Box-Cox transformations but means and other values are reported in the original scale as well as bu ac^{-1} for yield data to compare with other harvest records. A mixed model was used to analyze data. Rotation and fertilizer were used as fixed factorial treatments to test for treatment effects and interaction effects and block was used as a random effect. With the results from this test, multiple comparisons were run to determine any significant differences within treatment factors using a Tukey's HSD test for the fertilizer treatment and interaction effects if significance was detected.

Normalized crop yield data were also used in linear regression analyses to determine the influence of plant available nutrients on crop yields when treatment effects were shown to be significant. Linear regressions were also analyzed with raw water sample data to determine if relationships were positive or negative.

CHAPTER 3

RESULTS

NUTRIENT LEACHING

NITRATE-N

There were no significant impacts on nitrate-N leaching due to the rotation, fertilizer, or interaction factors in the March-June 2022 winter wheat sampling season or the June-October 2022 soybean season.

In the October 2022-April 2023 bare fallow/cover crop season the rotation was significant (Figure 3.1). Nitrate-N leaching in bare fallow rotations (4.795 kg ha $^{-1}$) was significantly greater than cover crop rotations (1.476 kg ha^{-1}) by a difference of 3.319 kg ha^{-1} (105.80%) (Table 3.1).

In the May-October 2023 corn season, the rotation factor was also significant (Figure 3.1). Nitrate-N leaching in bare fallow (9.225 kg ha $^{-1}$) was significantly greater than cover crop rotations (4.643 kg ha^{-1}) by a difference of 4.582 kg ha^{-1} (66.08%) (Table 3.1).

In the October 2023-March 2024 winter wheat sampling season the fertilizer factor was significant (Figure 3.1). Nitrate-N leaching in no fertilizer plots (3.409 kg ha^{-1}) was significantly greater than low fertilizer plots (0.766 kg ha^{-1}) by a difference of 2.643 kg ha^{-1} (126.61%), medium fertilizer plots (1.002 kg ha^{-1}) by a difference of 2.407 kg ha^{-1} (109.14%) and high fertilizer plots (1.388 kg ha^{-1}) by a difference of 2.021 kg ha^{-1} (51.12%) (Table 3.1).

For the duration of a full crop rotation from March 2022-March 2024 the rotation and season factors were significant (Figure 3.2). Nitrate-N leaching in bare fallow plots (3.905 kg ha^{-1}) was significantly greater than cover crop plots (2.026 kg ha^{-1}) by a difference of 1.879 kg ha^{-1} (63.36%) (Table 3.1).

Nitrate-N leaching in the summer 2023 corn season (6.961 kg ha^{-1}) was significantly greater than the winter 2021-2022 winter wheat season (2.279 kg ha^{-1}) by a difference of 4.682 kg ha^{-1} (101.34%), and significantly greater than the summer 2022 soybeans season (0.769 kg ha^{-1}) by a difference of 6.192 kg ha^{-1} 160.21%), and the winter 2022-2023 bare fallow/cover crop season (3.144 kg ha^{-1}) by a difference of 3.817 kg ha^{-1} (75.55%). Nitrate-N leaching in the winter 2022-2023 bare fallow/cover crop season was also significantly greater than the winter 2021-2022 winter wheat season by a difference of 0.865 kg ha^{-1} (31.90%) (Table 3.1).

Nitrate-N leaching averaged 2.972 kg ha^{-1} for the full crop rotation and ranged from an average of 1.314 kg ha^{-1} in C-R-S-R plots to an average of 5.436 kg ha^{-1} per rain event in C-Wl-S-N plots, a difference of 4.122 kg ha^{-1} (122.13%) (Table 3.1).

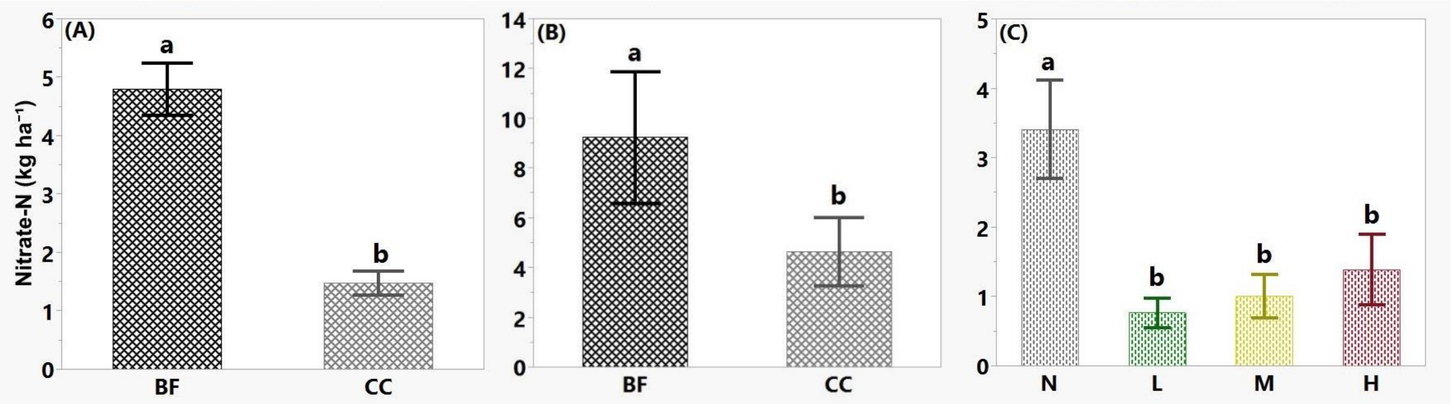

Figure 3.1. Nitrate-N leaching as influenced by the rotation factor in the winter 2022-2023 bare fallow/cover crop season (A), and the summer 2023 corn season (B), and by the fertilizer factor in the winter 2023-2024 winter wheat season (C). Different letters indicate significant difference at $p<0.05$. Error bars represent one standard error.

Table 3.1. Mean nitrate-N leaching (kg ha^{-1}) for treatment, fertilizer factor, rotation factor, and overall during each crop season and for the March 2022-March 2024 sampling period.

		Winter Wheat (2021-2022)			Soybeans (2022)			BF/CC (2022-2023)			Corn (2023)			Winter Wheat (2023-2024)			Sampling Period (2022-2024)		
		Rotation			Rotation			Rotation			Rotation			Rotation			Rotation		
		BF	CC	Mean	BF	CC	Mean	BF	CC	Mean	BF	CC	Mean	BF	CC	Mean	BF	CC	Mean
Fertilizer	N	1.358	0.865	1.111	0.574	0.655	0.611	4.726	0.898	2.794	10.214	5.474	7.844	4.756	2.062	3.409	10.214	5.474	7.844
	L	1.387	2.289	1.827	1.123	1.014	1.078	8.014	2.721	5.443	12.895	3.944	8.956	0.611	0.942	0.766	12.895	3.944	8.956
	M	2.660	2.450	2.554	1.576	1.738	1.675	3.777	1.607	2.713	7.682	5.311	6.440	0.875	1.147	1.002	7.682	5.311	6.440
	H	3.149	3.636	3.395	0.452	1.137	0.794	2.516	0.743	1.613	5.148	4.048	4.574	2.060	0.715	1.388	5.148	4.048	4.574
	Mean	2.170	2.387	2.279	0.910	1.164	0.769	4.795	1.477	3.144	9.225	4.643	6.961	2.076	1.246	1.675	9.225	4.643	6.961

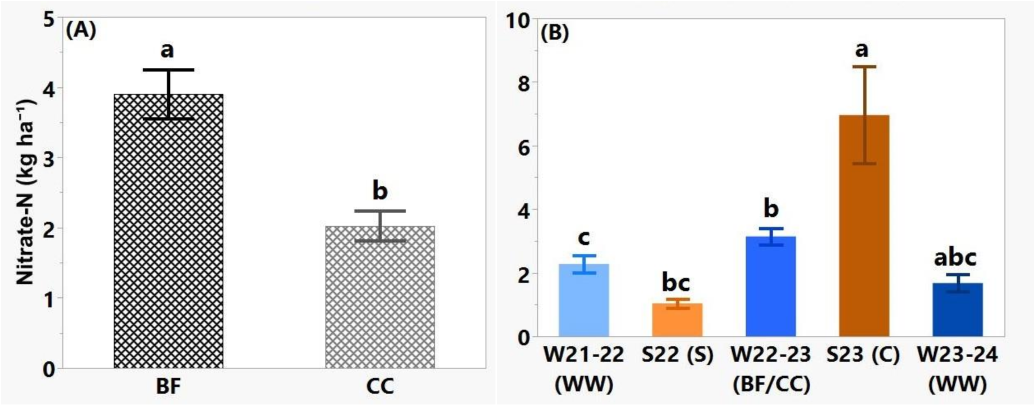

Figure 3.2. Nitrate-N leaching as influenced by rotation (A) and season (B) for the duration of the March 2022-March 2024 sampling period. Different letters indicate significant difference at $p<0.05$. Error bars represent one standard error.

AMMONIUM-N

There were no significant impacts on ammonium-N leaching in the March 2021-June 2022 winter wheat sampling season, June-October 2022 soybean season, October 2022-April 2023 bare fallow/cover crop season, or the May-October 2023 corn season due to the rotation, fertilizer, or interaction factors.

In the October 2023-March 2024 winter wheat sampling season the fertilizer factor was significant (Figure 3.4). Ammonium-N leaching in no fertilizer plots (0.131 kg ha^{-1}) was significantly greater than low fertilizer plots (0.0555 kg ha^{-1}) by a difference of 0.0755 kg ha^{-1} (80.97%) (Table 3.2).

For the duration of the March 2022-2024 sampling period, there was no significant impact on ammonium-N leaching due to the rotation or other interaction factors, but the fertilizer, season, and season*fertilizer interaction factors were significant despite no significant differences being detected among the fertilizer or season*fertilizer factors (Figure 3.5). However, ammonium-N leaching in no fertilizer plots (0.429 kg ha^{-1}) was nearly significantly less than low fertilizer plots (0.834 kg ha^{-1}, p=0.556) by a difference of 0.405 kg ha^{-1} (64.13%), and medium fertilizer plots (0.677 kg ha^{-1}, p=0.592) by a difference of 0.248 kg ha^{-1} (44.85%) (Table 3.2).

Ammonium-N leaching in the summer 2023 corn season (2.253 kg ha^{-1}) was significantly greater than the summer 2022 soybean season (0.481 kg ha^{-1}) by a difference of 1.772 kg ha^{-1} (129.63%), the winter 2022-2023 bare fallow/cover crop season (0.216 kg ha^{-1}) by a difference of 2.037 kg ha^{-1} (165.01%), and the winter 2023-2024 winter wheat season (0.0978 kg ha^{-1}) by a difference of 2.155 kg ha^{-1} (183.36%). Ammonium-N leaching in the winter 2021-2022 winter wheat season (0.937 kg ha^{-1}) was significantly greater than the summer 2022 soybean season by a difference of 0.456 kg ha^{-1} (64.32%) and the winter 2023-2024 winter wheat season by a difference of 0.839 kg ha^{-1} (162.20%) (Table 3.2).

Ammonium-N leaching for the full crop rotation averaged 0.674 kg ha^{-1} and ranged from an average of 0.293 kg ha^{-1} in C-R-S-R plots to an average of 0.937 kg ha^{-1} in C-Wh-S-R plots, a difference of 0.644 kg ha^{-1} (104.72%) (Table 3.2)

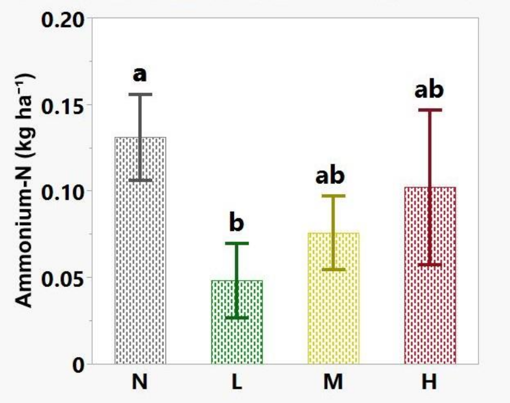

Figure 3.3. Ammonium-N leaching as influenced by rotation in the October 2023-March 2024 winter wheat sampling season. Different letters indicate significant difference at $p<0.05$. Error bars represent one standard error

Table 3.2. Mean ammonium-N leaching (kg ha^{-1}) for treatment, fertilizer factor, rotation factor, and overall during each crop season and for the March 2022-March 2024 sampling period.

		Winter Wheat (2021-2022)			Soybeans (2022)			BF/CC (2022-2023)			Corn (2023)			Winter Wheat (2023-2024)			Sampling Period (2022-2024)		
		Rotation			Rotation			Rotation			Rotation			Rotation			Rotation		
		BF	CC	Mean	BF	CC	Mean	BF	CC	Mean	BF	CC	Mean	BF	CC	Mean	BF	CC	Mean
Fertilizer	N	0.193	0.171	0.182	0.765	0.333	0.569	0.262	0.215	0.239	3.349	1.218	2.284	0.169	0.093	0.131	0.564	0.293	0.429
	L	0.667	1.413	1.025	0.149	1.931	0.883	0.280	0.164	0.226	3.556	2.082	2.907	0.072	0.028	0.055	0.760	0.921	0.834
	M	0.824	1.411	1.121	0.357	0.169	0.242	0.120	0.149	0.134	1.827	2.361	2.107	0.048	0.125	0.081	0.537	0.813	0.677
	H	0.509	0.667	1.232	0.006	0.213	0.110	0.368	0.157	0.259	1.656	1.645	1.651	0.208	0.055	0.119	0.527	0.937	0.741
	Mean	0.572	1.297	0.937	0.377	0.588	0.481	0.258	0.172	0.216	2.646	1.851	2.253	0.116	0.078	0.098	0.603	0.746	0.674

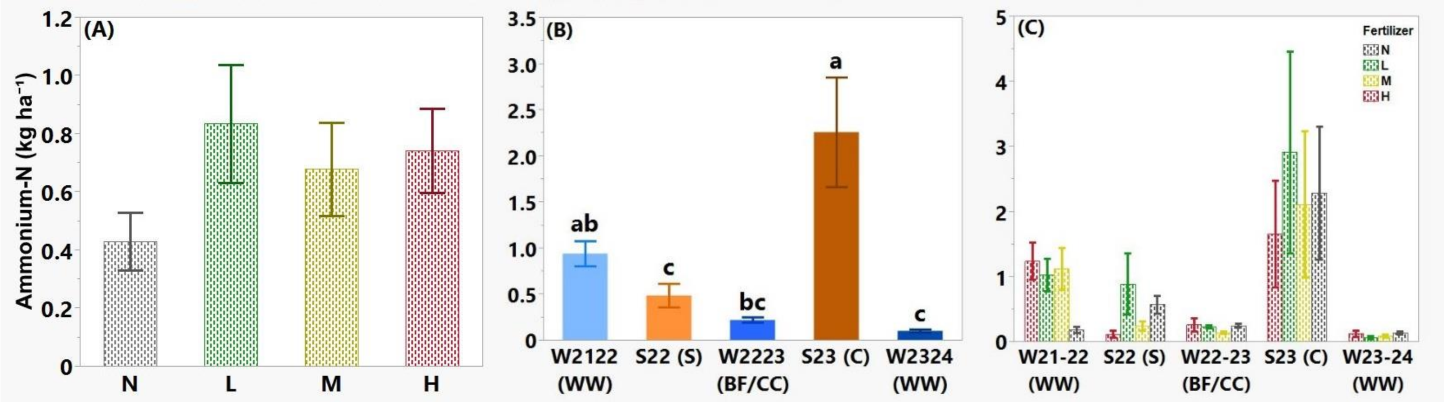

Figure 3.4. Ammonium-N leaching as influenced by fertilizer (A), season (B), and fertilizer*season (C) for the duration of the March 2022-March 2024 sampling period. Different letters indicate significant difference at p<0.05. Error bars represent one standard error.

DRP

There were no significant impacts on DRP leaching due to the rotation, fertilizer, or interaction factors in any individual sampling season.

For the duration of the March 2022-March 2024 sampling period, only the season factor was highly significant (Figure 3.7). DRP leaching was greatest in the winter 2023-2024 winter wheat sampling season (0.266 kg ha^{-1}) and significantly greater than all but the 2021-2022 winter wheat sampling season by a range of 0.084 kg ha^{-1} (37.50%) in the summer 2022 soybean season to 0.0790 kg ha^{-1} (108.41%) in the summer 2023 corn season. DRP leaching in the 2021-2022 winter wheat sampling season was significantly greater than these seasons by a range of 0.008 kg ha^{-1} (4.30%) to 0.111 kg ha^{-1} (82.53%) (Table 3.3).

DRP leaching for the full crop rotation averaged 0.151 kg ha^{-1} and ranged from an average of 0.0982 kg ha^{-1} in C-Wh-S-N plots to an average of 0.186 kg ha^{-1} in C-N-S-N plots, a difference of 0.0878 kg ha^{-1} or 61.79% (Table 3.3).

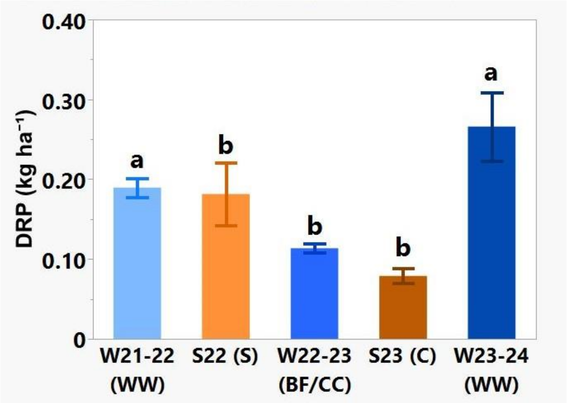

Figure 3.5. DRP leaching as influenced by season for the duration of the March 2022-March 2024 sampling period. Different letters indicate significant difference at $p<0.05$. Error bars represent one standard error.

Table 3.3. Mean DRP leaching (kg ha^{-1}) for treatment, fertilizer factor, rotation factor, and overall during each crop season and for the March 2022-March 2024 sampling period.

		Winter Wheat (2021-2022)			Soybeans (2022)			BF/CC (2022-2023)			Corn (2023)			Winter Wheat (2023-2024)			Sampling Period (2022-2024)		
		Rotation			Rotation			Rotation			Rotation			Rotation			Rotation		
		BF	CC	Mean	BF	CC	Mean	BF	CC	Mean	BF	CC	Mean	BF	CC	Mean	BF	CC	Mean
Fertilizer	N	0.226	0.148	0.187	0.259	0.109	0.191	0.142	0.112	0.127	0.123	0.069	0.096	0.247	0.330	0.289	0.185	0.135	0.161
	L	0.153	0.222	0.187	0.042	0.551	0.252	0.148	0.106	0.127	0.087	0.079	0.084	0.369	0.125	0.255	0.148	0.175	0.161
	M	0.218	0.198	0.208	0.299	0.132	0.197	0.093	0.126	0.110	0.064	0.075	0.069	0.259	0.382	0.317	0.159	0.162	0.161
	H	0.133	0.218	0.176	0.008	0.077	0.043	0.080	0.101	0.090	0.073	0.066	0.069	0.145	0.249	0.197	0.098	0.146	0.123
	Mean	0.180	0.199	0.190	0.162	0.202	0.182	0.116	0.111	0.114	0.086	0.072	0.079	0.259	0.274	0.266	0.148	0.155	0.151

PLANT AVAILABLE NUTRIENTS

NITRATE-N

There were no significant impacts on plant available nitrate-N concentrations due to the rotation, fertilizer, or interaction factors in the October 2021-June 2022 winter wheat sampling season or the October 2023-March 2024 winter wheat sampling season.

In the June-October 2022 soybean season the fertilizer factor was significant (Figure 3.8). Plant available nitrate-N concentrations in no fertilizer plots (3.332 mg L^{-1}) were significantly less than high fertilizer plots (7.233 mg L^{-1}) by a difference of 3.901 mg L^{-1} (73.85%) (Table 3.4).

In the October 2022-April 2023 bare fallow/cover crop season the rotation factor was significant (Figure 3.8). Plant available nitrate-N concentrations in bare fallow plots (10.535 mg L^{-1}) was significantly greater than cover crop plots (3.200 mg L^{-1}) by a difference of 7.335 mg L^{-1} (106.81%) (Table 3.4).

In the May-October 2023 corn season the rotation factor was also significant (Figure 3.8). Plant available nitrate-N concentrations in bare fallow plots (15.400 mg L^{-1}) was significantly greater than cover crop plots (5.834 mg L^{-1}) by a difference of 9.566 mg L^{-1} (90.14%) (Table 3.4).

For the duration of a full crop rotation from March 2022-March 2024 the rotation and season factors were highly significant, and the rotation*season interaction factor was significant (Figure 3.9). Plant available nitrate-N concentrations in bare fallow plots (8.078 mg L^{-1}) was significantly less than cover crop plots (3.278 mg/L) by a difference of 4.800 mg L^{-1} (84.54%) (Table 3.4).

Plant available nitrate-N concentrations in the winter 2021-2022 winter wheat season (3.153 mg L^{-1}) was significantly less than the summer 2022 soybean season (4.818 mg L^{-1}) by a difference of 1.665 mg L^{-1} (41.78%) and the summer 2023 corn season (10.143 mg L^{-1}) by 6.99 mg L^{-1} (105.14%). Plant available nitrate-N concentrations in the winter 2023-2024 winter wheat season (1.788 mg L^{-1}) was significantly less than the winter 2022-2023 bare fallow/cover crop season (6.733 mg L^{-1}) by a difference of 4.945 mg L^{-1} (116.07%) and highly significantly less than the summer 2022 soybean season by a difference of 3.03 mg L^{-1} (91.74%) and the summer 2023 corn season by a difference of 8.355 mg L^{-1} (140.06%) (Table 3.4).

Significance was detected between 15 of 45 rotation*season combinations, five of which were highly significant. Differences in plant available nitrate-N concentrations among these combinations ranged from 0.639 mg L^{-1} (23.66%) between the cover crop rotation plots in the winter 2022-2023 bare fallow/cover crop season and the bare fallow rotation plots in the winter 2023-2024 winter wheat season and 14.174 mg L^{-1} (170.50%) between the bare fallow rotation plots in the summer 2023 corn season and the cover crop rotation plots in the winter 2023-2024 winter wheat season (Table 3.4).

Plant available nitrate-N concentrations for the total crop rotation averaged 5.623 mg L^{-1} and ranged from an average of 2.590 mg L^{-1} in C-Wl-S-R plots to an average of 8.597 mg L^{-1} in C-Wm-S-N plots, a difference of 6.007 mg L^{-1} (107.38%) (Table 3.4).

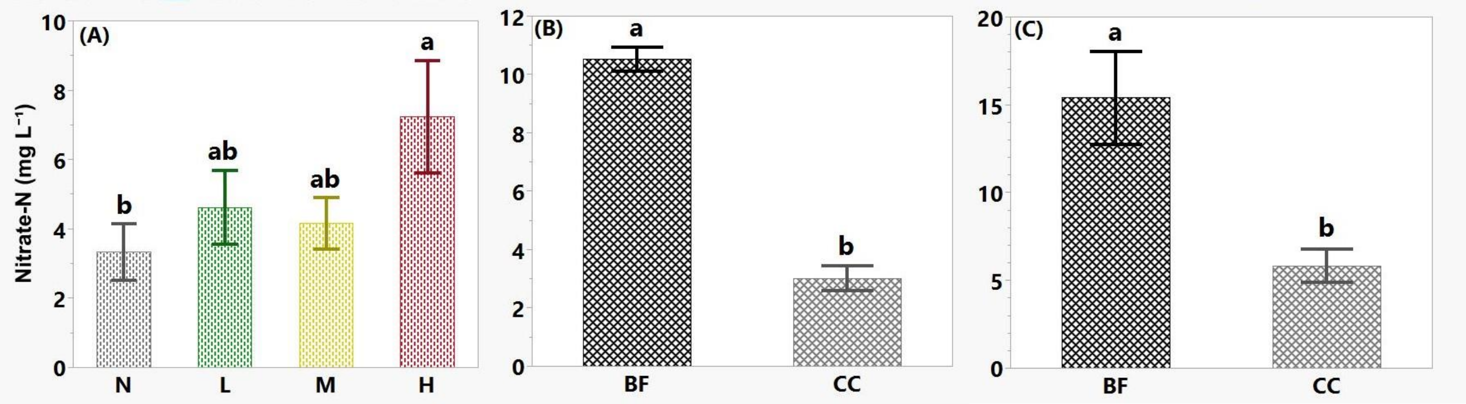

Figure 3.6. Plant available nitrate-N concentrations as influenced by the fertilizer factor in the summer 2022 soybean season (A), and the rotation factor in the winter 2022-2023 winter wheat season (B), and in the summer 2023 corn season (C). Different letters indicate significant difference at $p<0.05$. Error bars represent one standard error.

Table 3.4. Mean plant available nitrate-N concentrations (mg L^{-1}) for treatment, fertilizer factor, rotation factor, and overall during each crop season and for the March 2022-March 2024 sampling period.

		Winter Wheat (2021-2022)			Soybeans (2022)			BF/CC (2022-2023)			Corn (2023)			Winter Wheat (2023-2024)			Sampling Period (2022-2024)		
		Rotation			Rotation			Rotation			Rotation			Rotation			Rotation		
		BF	CC	Mean	BF	CC	Mean	BF	CC	Mean	BF	CC	Mean	BF	CC	Mean	BF	CC	Mean
Fertilizer	N	4.278	3.085	3.682	4.605	1.742	3.332	8.995	3.486	6.157	16.265	6.095	11.384	5.402	2.053	3.258	8.491	3.359	5.828
	L	1.969	1.786	1.875	5.064	4.283	4.617	12.190	2.589	7.080	9.075	4.203	6.051	1.622	0.470	1.084	7.003	2.590	4.637
	M	3.381	2.242	2.830	3.059	5.648	4.168	10.924	3.239	7.259	20.495	7.594	14.045	2.357	1.232	1.940	8.596	3.720	6.353
	H	4.275	4.343	4.309	9.575	4.890	7.233	10.137	2.738	6.438	14.791	9.075	9.698	1.336	1.082	1.190	8.149	3.513	5.696
	Mean	3.447	2.860	3.153	5.547	4.040	4.818	10.535	3.020	6.733	15.400	5.834	10.143	2.381	1.226	1.788	8.078	3.278	5.623

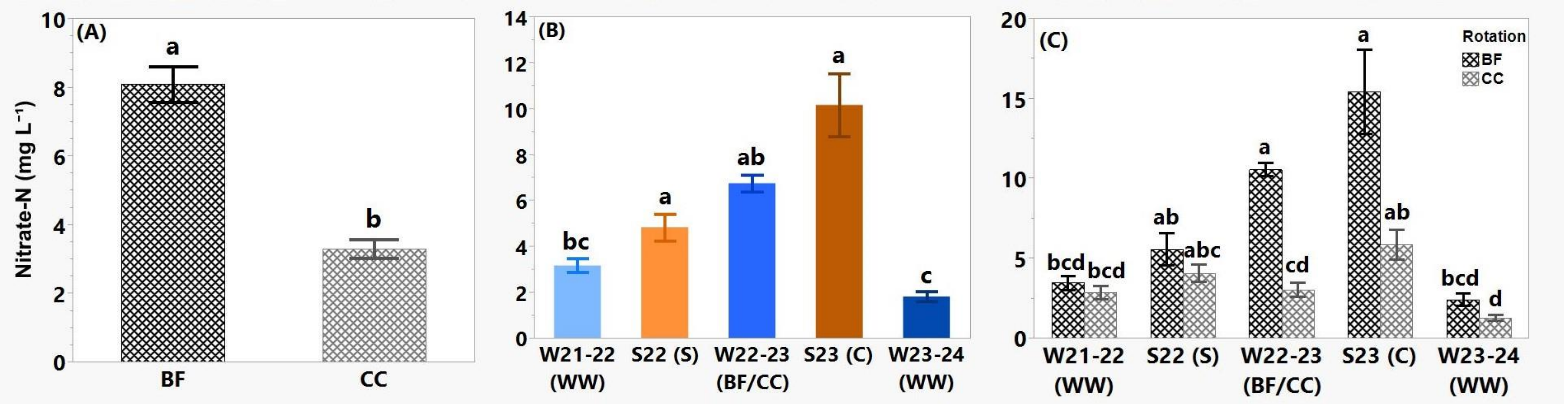

Figure 3.7. Plant available nitrate-N concentrations as influenced by rotation (A), season (B), and rotation*season interaction for the duration of the March 2022-March 2024 sampling period. Different letters indicate significant difference at $p<0.05$. Error bars represent one standard error.

AMMONIUM-N

There were no significant impacts on plant available ammonium-N concentrations due to the rotation, fertilizer, or interaction factors in the October 2021-June 2022 winter wheat sampling season, the October 2022-April 2023 bare fallow/cover crop season, the May-October 2023 corn season, or the October 2023-March 2024 winter wheat sampling season.

In the June-October 2022 soybean season the fertilizer factor was significant (Figure 3.11). Plant available ammonium-N concentrations in no fertilizer plots (0.0460 mg L^{-1}) were significantly less than low fertilizer plots (0.0759 mg L^{-1}) by a difference of 0.0299 mg L^{-1} (49.06%), medium fertilizer plots (0.0733 mg L^{-1}) by a difference of 0.0273 mg L^{-1} (45.77%), and high fertilizer plots (0.0755 mg L^{-1}) by a difference of 0.0295 mg L^{-1} (48.56%) (Table 3.5).

For the duration of a full crop rotation from March 2022-March 2024 the season factor was significant (Figure 3.12). Plant available ammonium-N concentrations in the winter 2023-2024 winter wheat sampling season (0.0361 mg L^{-1}) were highly significantly less than all other seasons, ranging from a difference of 0.0304 mg L^{-1} (59.21%) between the summer 2022 soybean season and 0.3819 mg L^{-1} (168.18%) between the summer 2023 corn season (Table 3.5).

Plant available ammonium-N concentrations averaged 0.1390 mg L^{-1} for the total crop rotation ranged from an average of 0.0878 mg L^{-1} in C-Wl-S-R plots to an average of 0.215 mg L^{-1} in C-N-S-N plots, a difference of 0.1270 mg L^{-1} (84.02%) (Table 3.5). Plant available ammonium-N concentrations had a significant negative relationship with precipitation since fertilizer, a highly significant negative relationship with weekly precipitation, and a highly significant positive relationship with weekly soil temperature (Figure 3.13).

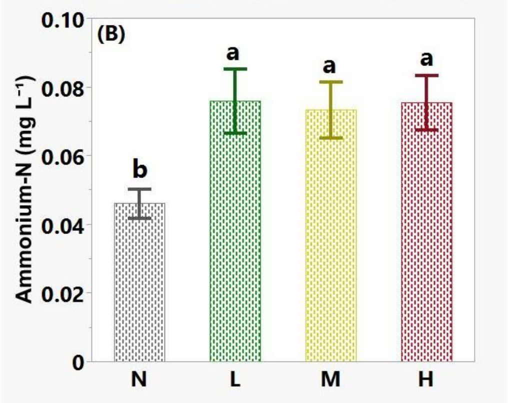

Figure 3.8. Plant available ammonium-N concentrations as influenced by the fertilizer factor in the summer 2022 soybean season. Different letters indicate significant difference at $p<0.05$. Error bars represent one standard error.

Table 3.5. Mean plant available ammonium-N concentrations (mg L^{-1}) for treatment, fertilizer factor, rotation factor, and overall during each crop season and for the March 2022-March 2024 sampling period.

		Winter Wheat (2021-2022)			Soybeans (2022)			BF/CC (2022-2023)			Corn (2023)			Winter Wheat (2023-2024)			Sampling Period (2022-2024)		
		Rotation			Rotation			Rotation			Rotation			Rotation			Rotation		
		BF	CC	Mean	BF	CC	Mean	BF	CC	Mean	BF	CC	Mean	BF	CC	Mean	BF	CC	Mean
Fertilizer	N	0.0373	0.0590	0.0486	0.0453	0.0470	0.0460	0.0975	0.0960	0.0967	0.9686	0.4384	0.7141	0.0209	0.0471	0.0368	0.2154	0.1300	0.1786
	L	0.1114	0.0648	0.0881	0.0793	0.0733	0.0759	0.0972	0.1019	0.0998	0.4440	0.1557	0.2732	0.0224	0.0579	0.0390	0.1263	0.0878	0.1139
	M	0.0683	0.1095	0.0882	0.0674	0.0811	0.0733	0.1126	0.1655	0.1377	0.6105	0.4531	0.5284	0.0302	0.0267	0.0288	0.1380	0.1626	0.1633
	H	0.0773	0.0698	0.0737	0.0811	0.0698	0.0755	0.0987	0.1067	0.1028	0.4508	0.0591	0.2234	0.0287	0.0463	0.0388	0.1311	0.0695	0.1046
	Mean	0.0762	0.0761	0.0761	0.0662	0.0669	0.0665	0.1019	0.1168	0.1095	0.6261	0.2457	0.4180	0.0260	0.0459	0.0361	0.1634	0.1157	0.1390

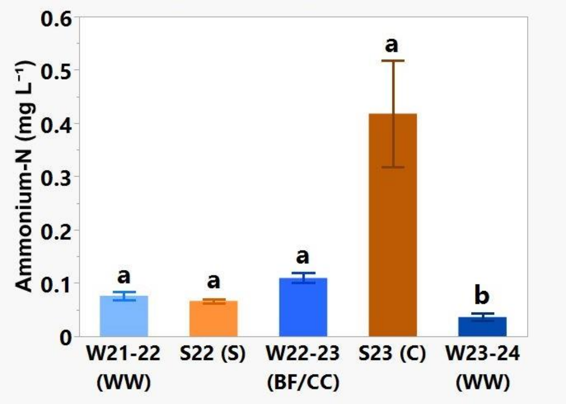

Figure 3.9 Plant available ammonium-N concentrations as influenced by season for the duration of the March 2022-March 2024 sampling period. Different letters indicate significant difference at $p<0.05$. Error bars represent one standard error.

DRP

There were no significant impacts on plant available DRP concentrations due to the rotation, fertilizer, or interaction factors in the October 2021-June 2022 winter wheat sampling season, the October 2022-April 2023 bare fallow/cover crop season, or the October 2023-March 2024 winter wheat sampling season.

In the June-October 2022 soybean season the fertilizer factor was significant (Figure 3.14). Plant available DRP concentrations in no fertilizer plots (0.0788 mg L^{-1}) were significantly greater than medium fertilizer plots (0.0512 mg L^{-1}) by a difference of 0.0276 (42.46%) and high fertilizer plots (0.0615 mg L^{-1}) by a difference of 0.0173 (24.66%) (Table 3.6).

In the May-October 2023 corn season the fertilizer factor was significant (Figure 3.14). High fertilizer plots (0.0397 mg L^{-1}) were significantly less than no fertilizer plots (0.0553 mg L^{-1}) by a difference of 0.0156 mg L^{-1} (32.84%), and medium fertilizer plots (0.0514 mg L^{-1}) by a difference of 0.0117 mg L^{-1} (25.69%). (Table 3.6).

For the duration of a full crop rotation from March 2022-March 2024 the season factor was highly significant (Figure 3.15). Plant available DRP concentrations in the winter 2023-2024 winter wheat sampling season (0.0406 mg L^{-1}) were highly significantly less than the summer 2022 soybean season, and significantly less than all other seasons, ranging in difference from 0.0064 mg L^{-1} (14.64%) between the summer 2023 corn season and 0.0221 mg L^{-1} (42.87%) with the summer 2022 soybean season (Table 3.6).

Plant available DRP concentrations averaged 0.0521 mg L^{-1} for the total crop rotation ranged from an average of 0.0435 mg L^{-1} in C-Wh-S-R plots to an average of 0.0618 mg L^{-1} in C-Wm-S-R plots, a difference of 0.0183 mg L^{-1} (34.76%) (Table 3.6).

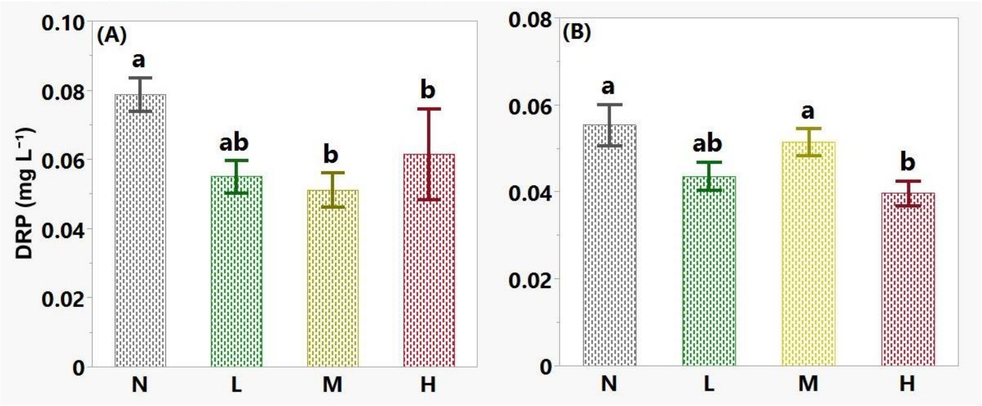

Figure 3.10. Plant available DRP concentrations as influenced by the fertilizer factor in the 2022 soybean season (A), and the summer 2023 corn season (B). Different letters indicate significant difference at $p<0.05$. Error bars represent one standard error.

Table 3.6. Mean plant available DRP concentrations (mg L^{-1}) for treatment, fertilizer factor, rotation factor, and overall during each crop season and for the March 2022-March 2024 sampling period.

		Winter Wheat (2021-2022)			Soybeans (2022)			BF/CC (2022-2023)			Corn (2023)			Winter Wheat (2023-2024)			Sampling Period (2022-2024)		
		Rotation			Rotation			Rotation			Rotation			Rotation			Rotation		
		BF	CC	Mean	BF	CC	Mean	BF	CC	Mean	BF	CC	Mean	BF	CC	Mean	BF	CC	Mean
Fertilizer	N	0.0485	0.0385	0.0435	0.0845	0.0717	0.0788	0.0597	0.0573	0.0585	0.0621	0.0480	0.0553	0.0568	0.0401	0.0461	0.0613	0.0505	0.0560
	L	0.0585	0.0505	0.0545	0.0592	0.0520	0.0550	0.0541	0.0502	0.0521	0.0420	0.0445	0.0436	0.0443	0.0339	0.0394	0.0516	0.0450	0.0489
	M	0.0520	0.0644	0.0580	0.0541	0.0473	0.0512	0.0536	0.0692	0.0610	0.0439	0.0589	0.0514	0.0460	0.0474	0.0465	0.0504	0.0618	0.0557
	H	0.0582	0.0534	0.0558	0.0749	0.0481	0.0615	0.0552	0.0508	0.0531	0.0415	0.0384	0.0397	0.0333	0.0320	0.0326	0.0511	0.0435	0.0479
	Mean	0.0546	0.0524	0.0535	0.0697	0.0553	0.0627	0.0556	0.0570	0.0563	0.0476	0.0465	0.0470	0.0441	0.0373	0.0406	0.0536	0.0506	0.0521

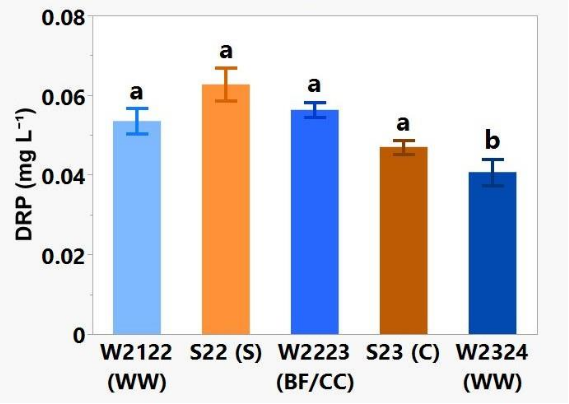

Figure 3.11. Plant available DRP concentrations as influenced by season for the duration of the March 2022-March 2024 sampling period. Different letters indicate significant difference at $p<0.05$. Error bars represent one standard error.

CROP YIELDS

SEASONAL

In the 2021-2022 winter wheat season, there were no significant impacts on winter wheat yields due to the rotation or interaction factors when excluding bare fallow and cover crop controls, but the fertilizer factor was significant. Winter wheat yields in low fertilizer plots (2.04 Mg DW ha^{-1}/30.28 bu ac^{-1}) were significantly lower than medium fertilizer plots (2.92 Mg DW ha^{-1}/43.37 bu ac^{-1}) by a difference of 0.88 Mg DW ha^{-1}/13.09 bu ac^{-1} (35.48%) (Figure 3.16) (Table 3.7). Winter wheat yields averaged 2.43 Mg DW ha^{-1}/36.13 bu ac^{-1} for the season and ranged from an average of 1.88 Mg DW ha^{-1}/28.01 bu ac^{-1} in C-Wl-S-N plots to an average of 2.96 Mg DW ha^{-1}/44.03 bu ac^{-1} in C-Wm-S-R plots, a difference of 1.08 Mg DW ha^{-1}/16.02 bu ac^{-1} (44.63%) (Table 3.7). Plant available nitrate-N concentrations had a significant positive relationship with winter wheat yields (Figure 3.17).

In the 2022 soybean season the fertilizer factor was highly significant (Figure 3.16). Soybean yields in no fertilizer plots (3.55 Mg DW ha^{-1}/52.75 bu ac^{-1}) were significantly greater than low fertilizer plots (3.07 Mg DW ha^{-1}/45.58 bu ac^{-1}) by a difference of 0.48 Mg DW ha^{-1}/7.17 bu ac^{-1} (14.50%), and significantly greater than medium fertilizer plots (2.70 Mg DW ha^{-1}/46.12 bu ac^{-1}) by a difference of 0.85 Mg DW ha^{-1}/6.63 bu ac^{-1} (27.2%), and high fertilizer plots (2.69 Mg DW ha^{-1}/46.03 bu ac^{-1}) by a difference of 0.86 Mg DW ha^{-1}/6.72 bu ac^{-1} (27.56%). Soybean yields averaged 3.20 Mg DW ha^{-1}/47.62 bu ac^{-1} for the season and ranged from an average of 2.95 Mg DW ha^{-1}/43.93 bu ac^{-1} in C-Wh-S-R plots to 3.57 Mg DW ha^{-1}/53.05 bu ac^{-1} in C-R-S-R plots, a difference of 0.62 Mg DW ha^{-1}/9.12 bu ac^{-1} (19.02%) (Table 3.7). Plant available ammonium-N had a significant negative relationship and plant available DRP concentrations had a significant positive relationship with soybean yields (Figure 3.17).

In the 2023 corn season the rotation factor was significant (Figure 3.16). Corn yields in bare fallow plots (12.47 Mg DW ha^{-1}/185.40 bu ac^{-1}) were significantly greater than cover crop plots (11.71 Mg DW ha^{-1}/174.19 bu ac^{-1}) by a difference of 0.76 Mg DW ha^{-1}/11.21 bu ac^{-1} (6.29%) (Table 3.7). Corn yields averaged 12.09 Mg DW ha^{-1}/179.79 bu ac^{-1} for the season and ranged from an average of 11.41 Mg DW ha^{-1}/169.69 bu ac^{-1} in C-Wh-S-R plots to an average of 12.80 Mg DW ha^{-1}/190.34 bu ac^{-1} in C-Wh-S-N plots, a difference of 1.39 Mg DW ha^{-1}/20.65 bu ac^{-1} (11.48%) (Table 3.7). Plant available nitrate-N concentrations had a significant positive relationship with corn yields. (Figure 3.17).

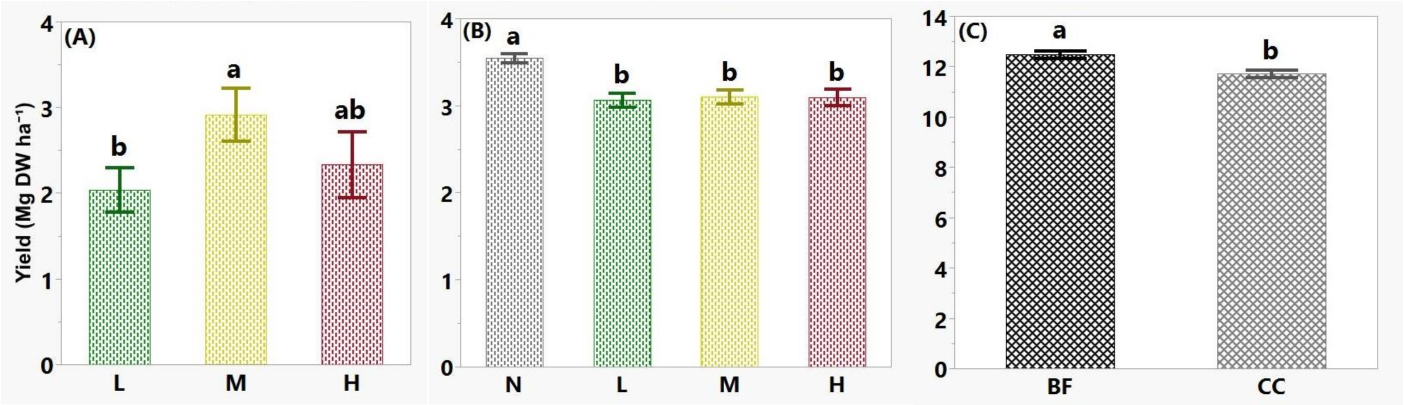

Figure 3.12. Crop yields as influenced by the fertilizer factor in the winter 2021-2022 winter wheat season (A), and in the summer 2022 soybean season (B), and by rotation in the summer 2023 corn season (C). Different letters indicate significant difference at $p<0.05$. Error bars represent one standard error.

Table 3.7. Mean crop yields in Mg DW ha^{-1} (A) and bu ac^{-1} (B) for treatment, fertilizer factor, rotation factor, and overall during each crop season.

(A)

		Winter Wheat (2021-2022)			Soybeans (2022)			Corn (2023		
		Rotation			Rotation			Rotation		
		BF	CC	Mean	BF	CC	Mean	BF	CC	Mean
Fertilizer	N	-	-	-	3.53	3.57	3.09	12.09	11.58	11.84
	L	1.88	2.19	2.04	3.08	3.05	3.07	12.55	11.87	12.21
	M	2.87	2.96	2.92	3.01	3.20	3.10	12.42	12.00	12.21
	H	2.14	2.53	2.34	3.24	2.95	3.55	12.80	11.41	12.11
	Mean	2.30	2.56	2.43	3.21	3.19	3.20	12.47	11.71	12.09

(B)

		Winter Wheat (2021-2022)			Soybeans (2022)			Corn (2023		
		Rotation			Rotation			Rotation		
		BF	CC	Mean	BF	CC	Mean	BF	CC	Mean
Fertilizer	N	-	-	-	52.45	53.05	52.75	179.82	172.20	176.01
	L	28.00	32.55	30.28	45.75	45.41	45.58	186.68	176.43	181.56
	M	42.71	44.03	43.37	44.71	47.53	46.12	184.75	178.45	181.60
	H	31.89	37.59	34.74	48.13	43.93	46.03	190.34	169.69	180.01
	Mean	34.20	38.06	36.13	47.76	47.48	47.62	185.40	174.19	179.79

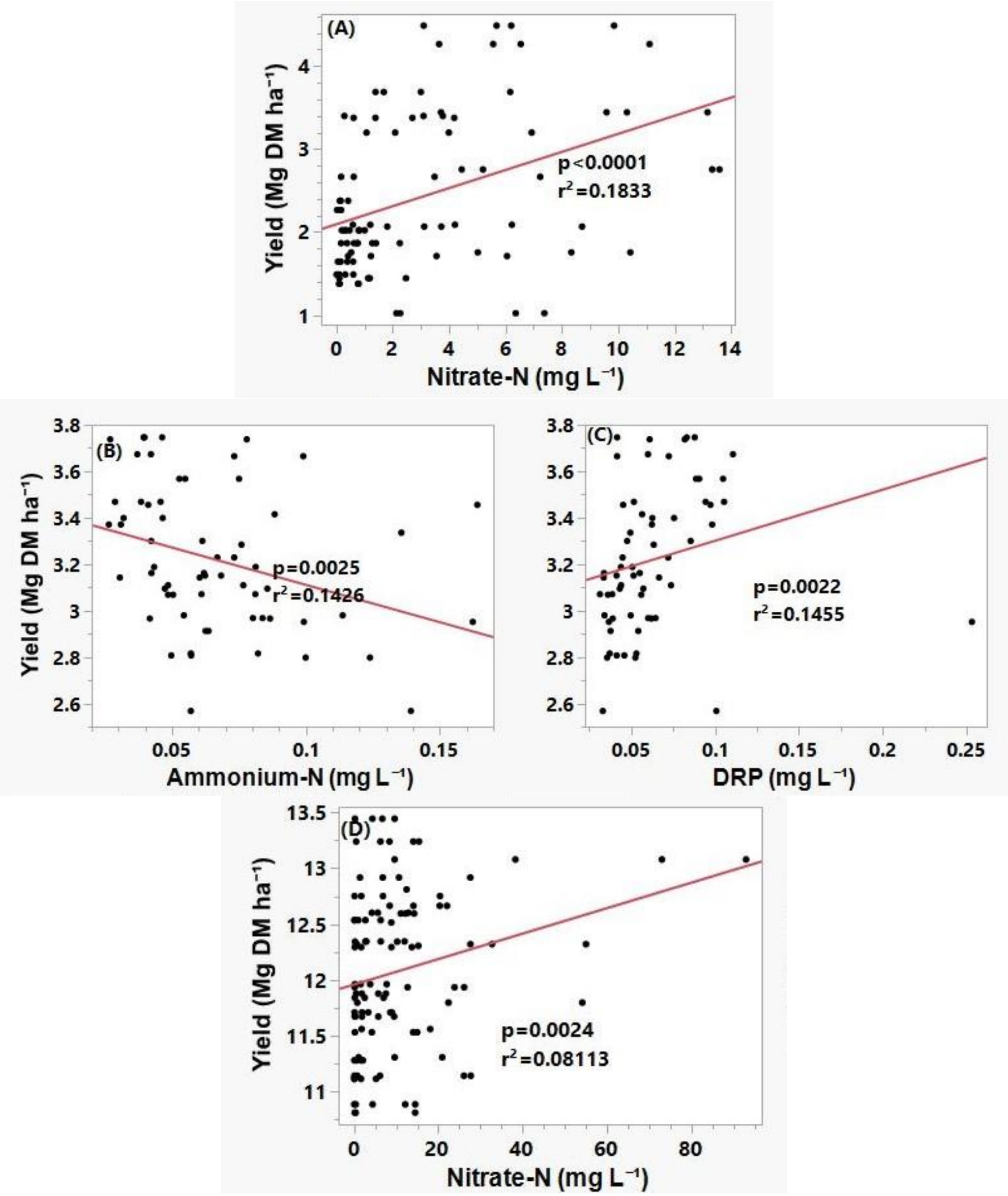

Figure 3.13. Linear regressions between winter wheat yields and plant available nitrate-N (A), soybean yields and ammonium-N (B), and DRP (C), and corn yields and nitrate-N concentrations (D) with trend line, p-value, and r^2 values.

TOTALS

There were no significant impacts on total cash crop yields due to the fertilizer or interaction factors, but the rotation factor was significant (Figure 3.20). Cash crop yields in bare fallow plots (15.68 Mg DW ha^{-1}/233.16 bu ac^{-1}) were significantly greater than cover crop plots

(14.91 Mg DW ha^{-1}/221.67 bu ac^{-1}) by a difference of 0.77 Mg DW ha^{-1}/11.49 bu ac^{-1} (5.03%) (Table 3.8). Cash crop yields averaged 15.29 Mg DW ha^{-1}/227.41 bu ac^{-1} for the combined soybean and corn seasons and ranged from an average of 14.37 Mg DW ha^{-1}/213.62 bu ac^{-1} in C-Wh-S-R plots to an average of 16.04 Mg DW ha^{-1}/238.47 bu ac^{-1} in C-Wh-S-N plots, a difference of 1.67 Mg DW ha^{-1}/24.85 bu ac^{-1} (10.98%) (Table 3.8). Plant available nitrate-N and DRP had a significant positive relationship with cash crop yields (Figure 3.19).

For total system crop yields, the fertilizer factor was highly significant (Figure 3.22). Combined 2021-2022 winter wheat, soybean, and corn yields in no fertilizer plots (15.38 Mg DW ha^{-1}/228.75 bu ac^{-1}) were significantly less than low fertilizer plots (17.31 Mg DW ha^{-1}/257.41 bu ac^{-1}) by a difference of 1.93 Mg DW ha^{-1}/228.66 bu ac^{-1} (11.81%) and significantly less than medium fertilizer plots (18.23 Mg DW ha^{-1}/271.08 bu ac^{-1}) by a difference of 2.85 Mg DW ha^{-1}/42.33 bu ac^{-1} (16.96%) and high fertilizer plots (17.54 Mg DW ha^{-1}/260.78 bu ac^{-1}) by a difference of 2.16 Mg DW ha^{-1}/532.03 bu ac^{-1} (13.12%) (Table 3.8). Total system yields averaged 17.12 Mg DW ha^{-1}/254.51 bu ac^{-1} for the combined 2021-2022 winter wheat, soybean, and corn seasons and ranged from an average of 15.15 Mg DW ha^{-1}/225.24 bu ac^{-1} in C-R-S-R plots to an average of 18.30 Mg DW ha^{-1}/272.17 bu ac^{-1} in C-Wm-S-N plots, a difference of 3.15 Mg DW ha^{-1}/46.93 bu ac^{-1} (18.83%) (Table 3.8). Plant available nitrate-N concentrations had a significant positive relationship with total system yields.

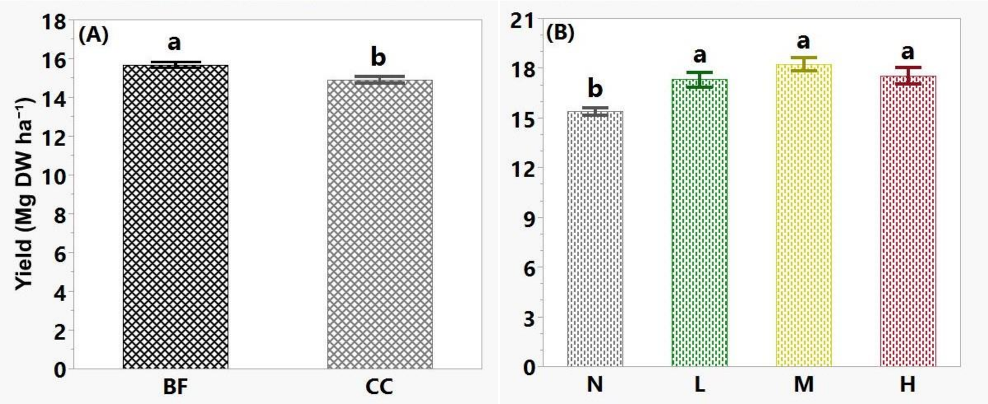

Figure 3.14. Crop yields as influenced by the rotation factor for total cash crops (A), and the fertilizer factor in total system crops (B). Different letters indicate significant difference at p<0.05. Error bars represent one standard error.

Table 3.8. Mean crop yields in Mg DW ha^{-1} (A) and bu ac^{-1} (B) for treatment, fertilizer factor, rotation factor, and overall for each crop total.

		(A)						**(B)**					
		Cash Crop Total (Soybeans & Corn)			System Total (All Crops)			Cash Crop Total (Soybeans & Corn)			System Total (All Crops)		
		Rotation			Rotation			Rotation			Rotation		
		BF	CC	Mean	BF	CC	Mean	BF	CC	Mean	BF	CC	Mean
Fertilizer	N	15.62	15.15	15.38	15.62	15.15	15.38	232.27	225.24	228.75	232.26	225.24	228.75
	L	15.63	14.92	15.28	17.51	17.11	17.31	232.43	221.84	227.13	260.43	254.39	257.41
	M	15.43	15.20	15.31	18.30	18.16	18.23	229.46	225.98	227.72	272.17	270.00	271.08
	H	16.04	14.37	15.20	18.18	16.89	17.54	238.47	213.62	226.05	270.36	251.21	260.78
	Mean	15.68	14.91	15.29	17.40	16.83	17.12	233.16	221.67	227.41	258.80	250.21	254.51

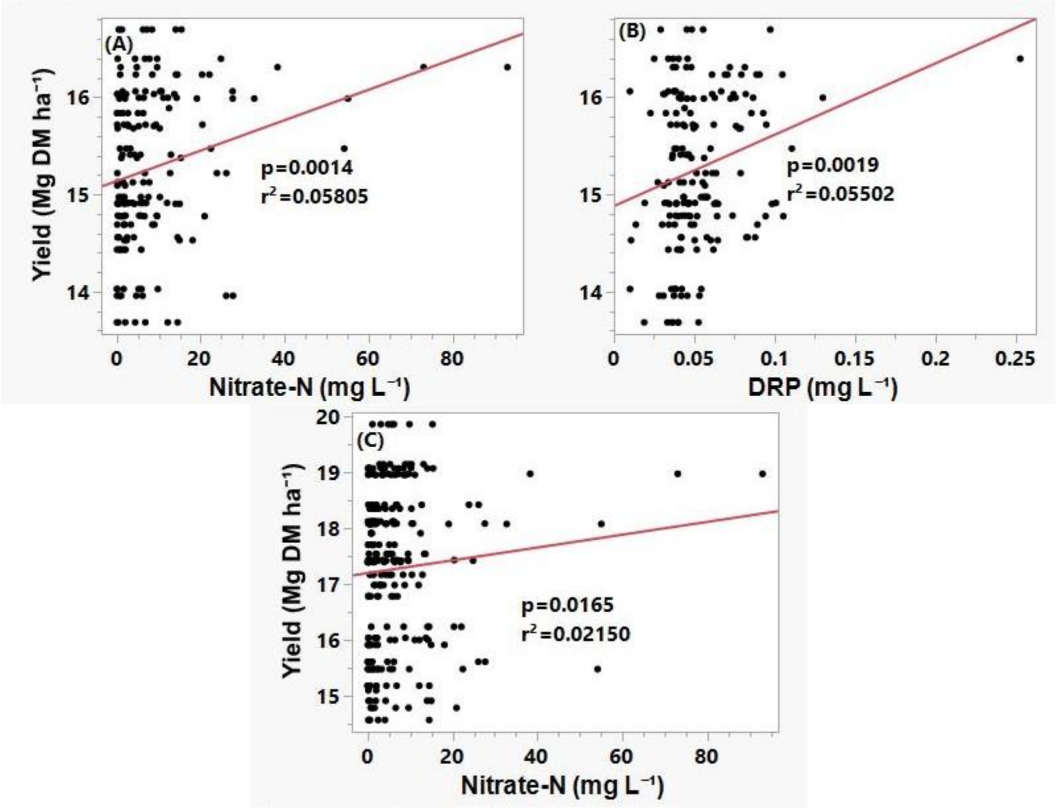

Figure 3.15. Linear regressions between combined cash crop yields and plant available nitrate-N (A), and DRP (B) and total crop yields and nitrate-N concentrations (C) with trend line, p-value, and r^2 values.

NITROGEN DYNAMICS

YIELD-BASED LEACHING

For the duration of the winter 2021-2022 winter wheat season, there were no significant impacts on yield-based nitrogen leaching due to the interaction factor, but the rotation and fertilizer factors were significant when no yield control plots were excluded (Figure 3.22). Winter wheat yield-based leaching in bare fallow plots (14.743 kg Mg^{-1}) was significantly less than cover crop plots (19.302 kg Mg^{-1}) by a difference of 4.559 kg Mg^{-1} (26.78%). Winter wheat yield-based leaching in high fertilizer plots (23.214 kg Mg^{-1}) was significantly greater than low fertilizer plots (14.594 kg Mg^{-1}) by a difference of 8.62 kg Mg^{-1} (45.60%), and medium fertilizer plots (13.258 kg Mg^{-1}) by a difference of 9.956 kg Mg^{-1} (54.60%) (Table 3.9). Winter wheat yield-based nitrogen leaching averaged 17.022 kg Mg^{-1} for the season and ranged from an average of 11.202 kg Mg^{-1} in C-Wl-S-N plots to an average of 26.272 kg Mg^{-1} in C-Wh-S-R plots, a difference of 15.07 kg Mg^{-1} or 80.43% (Table 3.9).

There were highly significant impacts on corn yield-based nitrogen leaching due to the rotation, fertilizer, and interaction factors (Figure 3.23). Corn yield-based leaching in bare fallow plots (3.028 kg Mg^{-1}) was significantly greater than cover crop plots (1.632 kg Mg^{-1}) by a difference of 1.396 kg Mg^{-1} (59.91%). Corn yield-based nitrogen leaching in no fertilizer and medium fertilizer plots was significantly different and in all other fertilizer combinations was significantly different, ranging from differences of in means of 0.406 kg Mg^{-1} (22.95%) between high fertilizer and medium fertilizer plots and 1.612 kg Mg^{-1} (67.96%) between high fertilizer plots and low fertilizer plots. Corn yield-based nitrogen leaching in C-Wm-S-N and C-Wm-S-R plots was not significantly different, but was significantly different in all other fertilizer combinations, ranging from differences in means from 0.049 kg Mg^{-1} (3.32%) between C-Wh-S-N and C-Wl-S-R plots and 3.256 kg Mg^{-1} (105.78%) between C-R-S-R and C-Wl-S-N plots. The seasonal mean was 2.330 kg Mg^{-1} (Table 3.9)

For combined winter wheat and corn yield-based nitrogen leaching, there were no significant impacts due to the rotation or interaction factors when excluding no fertilizer plots, but the fertilizer factor was significant (Figure 3.22). High fertilizer plots (24.780 kg Mg^{-1}) were significantly greater than medium fertilizer plots (15.230 kg Mg^{-1}) by a difference of 9.550 kg Mg^{-1} (47.74%). Total yield-based nitrogen leaching averaged 19.261 kg Mg^{-1} for the combined 2021-2022 winter wheat and corn seasons and plots with fertilizer applications and ranged from an average of 15.021 kg Mg^{-1} in C-Wm-S-R plots to an average of 27.905 kg Mg^{-1} in C-Wh-S-N plots, a difference of 12.884 kg Mg^{-1} (60.03%) (Table 3.10).

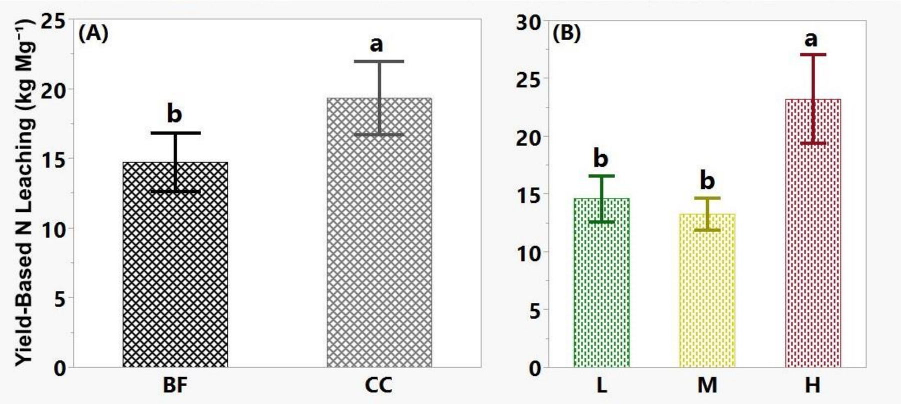

Figure 3.16. Winter wheat yield-based nitrogen leaching as influenced by the rotation factor (A), and the fertilizer factor (B). Different letters indicate significant difference at $p<0.05$. Error bars represent one standard error.

Table 3.9. Mean yield-based nitrogen leaching in kg Mg^{-1} for treatment, fertilizer factor, rotation factor, and overall for the 2021-2022 winter wheat season, 2023 corn season, and combined totals for plots with fertilizer applications in both seasons.

		Winter Wheat (2021-2022)			Corn (2023)			System Total (All Crops)		
		Rotation			Rotation			Rotation		
		BF	CC	Mean	BF	CC	Mean	BF	CC	Mean
Fertilizer	N	-	-	-	3.758	1.450	2.604	-	-	-
	L	11.202	17.987	14.594	4.706	1.650	3.178	15.908	19.637	17.773
	M	12.871	13.646	13.258	2.150	1.795	1.972	15.021	15.440	15.230
	H	20.155	26.272	23.214	1.499	1.633	1.566	21.654	27.905	24.780
	Mean	14.743	19.302	17.022	3.028	1.632	2.330	17.528	20.994	19.261

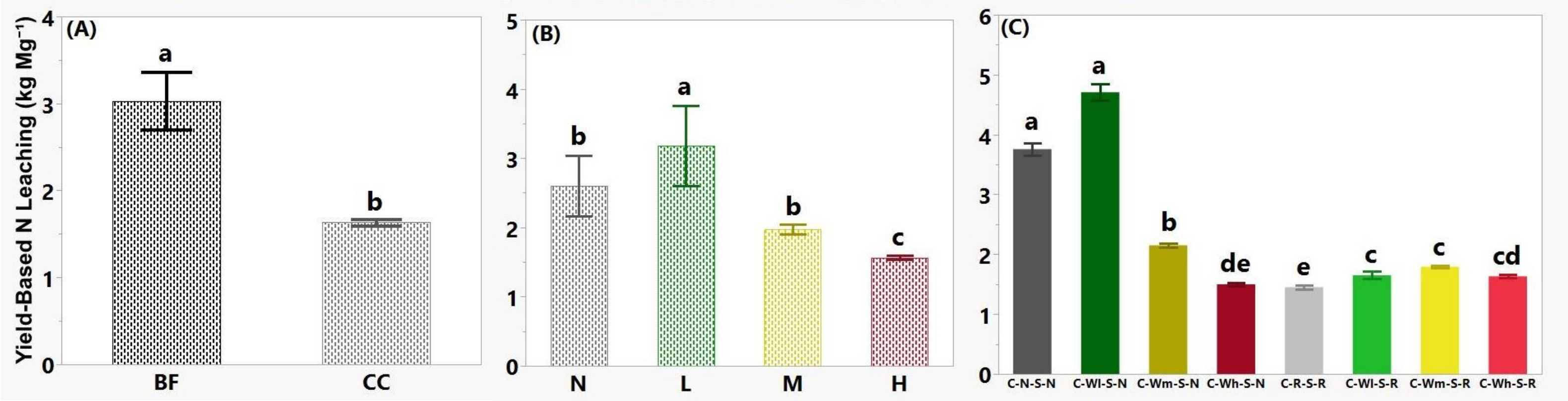

Figure 3.17. Corn yield-based nitrogen leaching as influenced by the rotation factor (A), the fertilizer factor (B), and overall treatment factor (C). Different letters indicate significant difference at $p<0.05$. Error bars represent one standard error.

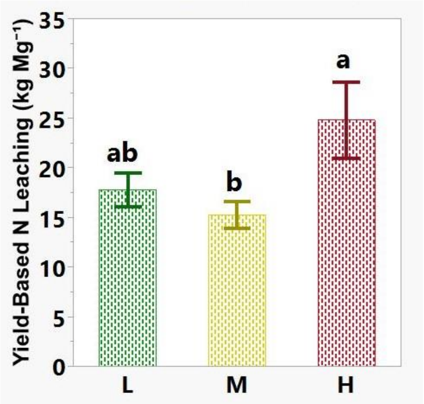

Figure 3.18. Total yield-based nitrogen leaching for combined seasons and plots where fertilizer was applied. Different letters indicate significant difference at $p<0.05$. Error bars represent one standard error.

NITROGEN UPTAKE

For the duration of the winter 2021-2022 winter wheat season, there were no significant impacts on plant nitrogen uptake due to the rotation or interaction factors, but the fertilizer factor was significant when no yield control plots were excluded (Figure 3.25). Plant nitrogen uptake in medium fertilizer plots (18.098 kg ha^{-1}) was significantly greater than low fertilizer plots (11.207 kg ha^{1}) by 6.891 kg ha^{-1} (47.03%) and high fertilizer plots (13.411 kg ha^{-1}) by 4.687 kg ha^{-1} (29.75%). Plant nitrogen uptake in this season averaged 14.238 kg ha^{-1} and ranged from an average of 10.244 kg ha^{-1} in C-Wl-S-N plots to 18.262 kg ha^{-1} in C-Wm-S-R plots, a difference of 3.994 kg ha^{-1} (56.26%) (Table 3.10).

In the summer 2022 soybean season, fertilizer was also significant (Figure 3.25). Plant nitrogen uptake in no fertilizer plots (100.803 kg ha^{-1}) was significantly greater than low fertilizer plots (78.350 kg ha^{-1}) by 22.453 kg ha^{-1} (25.07%), medium fertilizer plots (77.758 kg ha^{-1}) by 23.045 kg ha^{-1}, (25.82%), and high fertilizer plots (73.539 kg ha^{-1}) by 27.264 kg ha^{-1} (31.28%). Plant nitrogen uptake in this season averaged 82.613 kg ha^{-1} and ranged from an average of 66.612 kg ha^{-1} in C-Wh-S-R plots to an average of 103.891 kg ha^{-1} in C-N-S-N plots, a difference of 37.279 kg ha^{-1} (94.37%) (Table 3.10).

In the summer 2023 corn season, the rotation factor was significant (Figure 3.25). Plant nitrogen uptake in bare fallow plots (143.381 kg ha^{-1}) was significantly greater than in cover crop plots (134.716 kg ha^{-1}) by a difference of 8.665 kg ha^{-1} (6.23%). Plant nitrogen uptake in this season ranged from an average of 131.235 kg ha^{-1} in C-Wh-S-R plots to an average of 147.204 kg ha^{-1} in C-Wh-S-N plots, a difference of 15.969 ka ha^{-1} (11.47%) (Table 3.10).

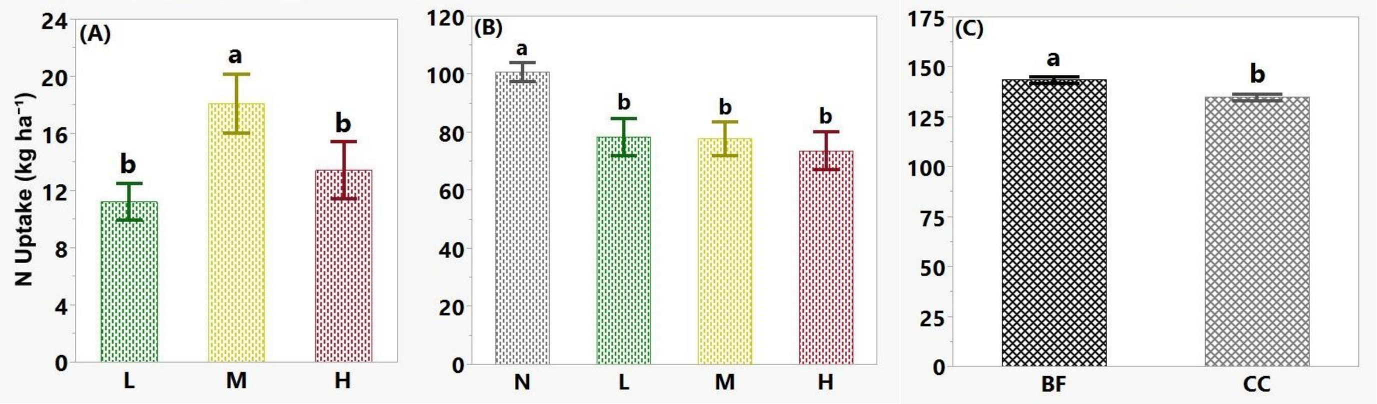

Figure 3.19. Plant nitrogen uptake as influenced by the fertilizer factor in the 2021-2022 winter wheat season (A) and 2022 soybean season (B), and by rotation in the 2023 corn season (C). Different letters indicate significant difference at $p<0.05$. Error bars represent one standard error.

Table 3.10. Mean plant nitrogen uptake (kg ha^{-1}) for treatment, fertilizer factor, rotation factor, and overall for the 2021-2022 winter wheat, 2022 soybean, and 2023 corn seasons.

		Winter Wheat (2021-2022)			Soybeans (2022)			Corn (2023)		
		Rotation			Rotation			Rotation		
		BF	CC	Mean	BF	CC	Mean	BF	CC	Mean
Fertilizer	N	-	-	-	103.891	97.715	100.803	139.065	133.172	136.119
	L	10.244	12.169	11.207	73.860	82.840	78.350	144.377	136.448	140.413
	M	17.933	18.262	18.098	71.840	83.676	77.758	142.880	138.008	140.444
	H	13.039	13.782	13.411	80.466	66.612	73.539	147.204	131.235	139.219
	Mean	13.739	14.738	14.238	82.513	82.711	82.613	143.381	134.716	139.049

PARTIAL NITROGEN BALANCE

For the duration of the winter 2021-2022 winter wheat season, there were no significant impacts on the partial nitrogen balance due to the rotation or interaction factor, but the fertilizer factor was significant when no yield control plots were excluded (Figure 3.26). The partial nitrogen balance in low fertilizer plots (108.724 kg ha^{-1}) was significantly less than medium fertilizer plots (169.084) by 60.360 kg ha^{-1} (43.46%) and high fertilizer plots (173.771 kg ha^{-1}) by 65.047 kg ha^{-1} (46.05%). The partial nitrogen balance in medium fertilizer plots was also significantly less than high fertilizer plots by 3.916 kg ha^{-1} (2.73%) (Table 3.11). The partial nitrogen balance for the season averaged 150.527 kg ha^{-1} and ranged from an average of 107.762 kg ha^{-1} in C-R-S-R plots to and average of 174.142 kg ha^{-1} in C-Wh-S-N plots, a difference of 66.380 kg ha^{-1} (47.09%) (Table 3.11).

In the summer 2023 corn season, the rotation factor was significant (Figure 3.26). Partial nitrogen leaching in bare fallow plots (56.619 kg ha^{-1}) was significantly less than in cover crop plots (65.284 kg ha^{-1}) by 8.665 kg ha^{-1} (14.22%). The partial nitrogen balance for the season ranged from an average of 52.796 kg ha^{-1} in C-Wh-S-N plots to an average of 68.766 kg ha^{-1} in C-Wh-S-R plots, a difference of 15.97 kg ha^{-1} (26.28%) (Table 3.11).

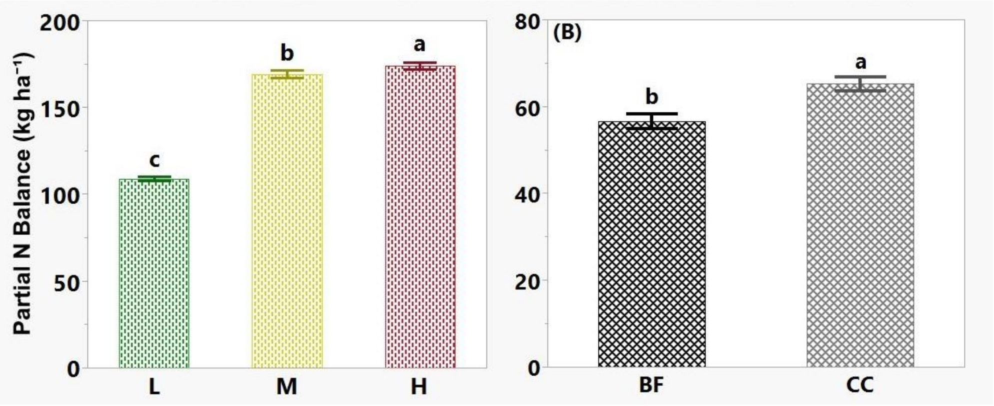

Figure 3.20. Partial nitrogen balance as influenced by the fertilizer factor in the 2021-2022 winter wheat season (A) and by the rotation factor in the 2023 corn season (B). Different letters indicate significant difference at $p<0.05$. Error bars represent one standard error.

Table 3.11. Mean partial nitrogen balance (kg ha^{-1}) for treatment, fertilizer factor, rotation factor, and overall for the 2021-2022 winter wheat and 2023 corn seasons.

		Winter Wheat (2021-2022)			Corn (2023)		
		Rotation			Rotation		
		BF	CC	Mean	BF	CC	Mean
Fertilizer	N	-	-	-	60.935	66.828	63.882
	L	109.686	107.762	108.724	55.624	63.552	59.588
	M	169.249	168.920	169.084	57.120	61.992	59.556
	H	174.142	173.400	173.771	52.796	68.766	60.781
	Mean	151.026	150.027	150.527	56.619	65.284	60.952

CHAPTER 4

DISCUSSION

In the 2021-2022 winter wheat sampling season, the use of fertilizers in winter wheat management did not significantly increase nutrient leaching compared to bare fallow and cover crop controls, despite nitrate-N and ammonium-N leaching in winter wheat plots being greater than control plots. Plant available ammonium-N and DRP trended higher in fertilized plots, likely due to the application of fertilizer, while plant available nitrate-N concentrations trended higher in no fertilizer and high fertilizer plots. This indicates that nitrate-N in no fertilizer plots was not being taken up by vegetation or at a slower rate in less densely planted cereal rye plots, but the continuous applications of fertilizer throughout the season in high fertilizer plots maintained higher levels of nitrate-N in the soil. Soil inorganic nitrogen in winter wheat plots, comprised primarily of nitrate-N, was reduced to a similar or greater amount in low and medium fertilizer plots, 24% and 62%, respectively, compared to the 34% reduction reported by Heggenstaller et al. (2008) in a study in Iowa, but was increased by 16% in high fertilizer plots. Given that nitrate-N leaching was 49-101% greater in winter wheat plots compared to control plots, the use of soil inorganic nitrogen by Heggenstaller et al. (2008) does not appear to be an accurate metric for potential nitrate-N leaching because it does not consider the addition of fertilizers and environmental conditions that control nutrient leaching from the soil.

Winter wheat yields in the 2021-2022 season (28.0-44.0 bu ac^{-1})were lower than the Jackson County average of 76.4 bu ac^{-1} in 2022 (NASS, 2022), due to poor establishment and higher than average amounts of precipitation throughout the growing season which could have contributed to waterlogged conditions. The high fertilizer plots had the lowest NUE as determined by yield-based leaching and partial nitrogen balances without significant improvements in yield or nitrogen uptake. Medium fertilizer plots had the greatest yields and nitrogen uptake while low fertilizer plots had the lowest partial nitrogen balances, but both had similar yield-based leaching amounts. Delayed fertilization in these plots improved NUE compared to high fertilizer plots, but low fertilizer treatments improved NUE while higher fertilizer rates in the medium fertilizer treatment improved yields. Efretuei et al. (2016) also reported that delaying fertilization until tillering maximized yields and NUE as determined by plant nitrogen uptake in a study in Ireland. Nitrogen uptake was lower than in triticale double crops reported by Heggenstaller et al. (2008), averaging 14 kg ha^{-1} compared to 85 kg ha^{-1}. This is most likely due to low winter wheat yields, but triticale has also been shown to have higher yields and protein content than winter wheat, which would also increase nitrogen uptake (Bishnoi & Hughes, 1979). The reason for the differences detected among rotation treatments is not known since rotation differences would not be implemented until the following winter.

In the 2023-2024 winter wheat sampling season, nitrate-N and ammonium-N leaching were greater in control plots to a significant degree in nitrate-N leaching and to significant degree between some plots in ammonium-N leaching. This discrepancy compared to the 2021-2022 may be due to the 2021-2022 sampling season producing leaching samples shortly after the two spring fertilizer applications in winter wheat plots, potentially overreporting averages without the early season data, while the 2023-2024 sampling season had limited leaching samples from months after the fall fertilizer application in high fertilizer plots, potentially underreporting averages from fertilizer events. Plant available nitrate-N trended higher in no fertilizer plots compared to fertilized plots but did not follow the same trend as the previous winter wheat season in high fertilizer plots or with plant available ammonium-N, which may change later in the season with subsequent fertilizer applications or could be due to more efficient nutrient usage of better-established winter wheat. Soil inorganic nitrogen was reduced in all winter wheat plots and to an even greater degree than the previous winter wheat season, averaging 50-98% compared to control plots while nitrate-N leaching was reduced by 84-127% in winter wheat plots compared to control plots. In this season, soil inorganic nitrogen followed a similar trend as nitrate-N leaching but was still not an accurate predictor. At the conclusion of this study, winter wheat had not been harvested for the 2023-2024 season.

Delayed planting in winter wheat plots negatively impacted soybean yields and nitrogen uptake, however the mean soybean yield for Jackson County in 2022 was 51.1 bu ac^{-1}, which was only slightly higher than the means for the plots (43.9-48.1 bu ac^{-1}), so this yield penalty was relatively small in comparison (NASS, 2023c). This penalty, averaging 9.8-10.8% of the county average, was also less than the predicted 12.4-19.8% yield penalty predicted for the planting date in the Midwest (Egli & Cornelius, 2009) and on the lower end of possible soybean yield reductions following a wheat double crop (Kyei-Boahen & Zhang, 2006). Residual plant available ammonium-N from fertilized 2021-2022 winter wheat led to increased plant available ammonium-N in those plots in the 2022 soybean season, which can also cause a reduction in soybean biological nitrogen fixation (Santachiara et al., 2019) that can lead to nitrogen stress later in the season (Salvagiotti et al., 2009). This may have also contributed to increased phosphorus uptake, leading to decreased plant available DRP in fertilized plots. Given the preference for ammonium over nitrate in soybeans (Daryanto et al., 2019), plant available nitrate-N did not influence soybean yields.

In the 2022-2023 bare fallow/cereal rye season, the presence of cereal rye in cover cropped plots led to significantly less nitrate-N leaching and plant available nitrate-N. DRP leaching in cover crop plots ranged from a reduction of 38% to an increase of 45% compared to bare fallow plots, an inconsistency that is also reported by other studies (Aronsson et al., 2016, Carver et al., 2022).

The effect of nitrate-N leaching and plant available nitrate-N concentrations carried over into the 2023 corn season, where the lower levels of plant available nitrate-N in cover cropped plots negatively impacted corn and total cash crop yields and corn nitrogen uptake in cover crop plots. The mean corn crop yield for Jackson County in 2023 was 165.2 bu ac^{-1} however, so these yields (169.7-178.5 bu ac^{-1}) were still higher than average in comparison. This 6% penalty in corn yields following cover crops compared to bare fallow plots was greater than the 3% average in a meta-analysis reported by Tonitto et al. (2006) but falls within the 95% confidence interval for the 69 studies that were analyzed. Due to higher corn yields and consequent nitrogen uptake, the partial nitrogen balance was higher in cover crop plots. The difference in yield-based nitrogen leaching due to rotation is due to the lower levels of leaching in cover crop plots, but the significance of fertilizer or the rotation*fertilizer interaction may be due to the high levels of variability in leaching between all plots. The reason for significant differences in plant available DRP detected among fertilizer treatments is not known because the only phosphorus applications and differences in the fertilizer treatment occurred over a year before the corn season.

For the whole crop rotations, the use of cover crops in the bare fallow/cover crop season had the most significant treatment effect for nitrate-N leaching and plant available nitrate-N. This practice reduced overall nitrate-N leaching by 63% compared to bare fallow rotations, which is only slightly below the mean leaching reduction in non-leguminous cover crops of 70% reported by Tonitto et al. (2006) and 68% reported by Nouri et al. (2022), but more than double what was predicted in the NLRS (2015). The season also influenced both, as well as the interaction of season and rotation in nitrate-N leaching, likely due to the crop residue that was present in the soil (Chen et al., 2014) and the increased nutrient uptake in cover crop plots (Blanco-Canqui et al., 2015). Following the corn season, which left behind carbon-rich residues that can cause nitrogen immobilization, the winter wheat seasons had some of the lowest nitrate-N leaching and plant available nitrate-N levels. The following soybean season also had low nitrate-N leaching due to corn and wheat residues in the soil but also had some of the highest plant available nitrate-N, which may be explained by reduced uptake by the soybeans. Soybean residue has a much lower C:N ratio that would allow for more nitrogen mineralization, which may explain the increase in nitrate-N leaching in the following bare fallow/cover crop season, particularly in bare fallow plots where no vegetation was taking up nutrients. In the corn season, the greatest amounts of nitrogen fertilizers were applied and less carbon-rich residues were present to cause immobilization, leading to the highest averages of nitrate-N leaching and plant available nitrate-N concentrations. In bare fallow plots, these rates were even higher due to the lack of nutrient scavenging from cover crops in the prior season and lack of cereal rye residue persisting on the surface to immobilize nitrogen.

Season was the most influential factor in ammonium-N, along with the fertilizer treatment in ammonium-N leaching. While not significant, ammonium-N leaching had the lowest average in no fertilizer plots, likely influenced by the low average in 2021-2022 winter wheat season. Plant available ammonium-N followed similar trends as nitrate-N by being lowest in seasons when more carbon-rich residues persisted and highest in seasons that follow soybeans. Ammonium-N leaching, however, was greatest in the 2021-2022 winter wheat season and 2023 corn season when sampling occurred soon after fertilization events and lower in seasons when fertilizer was not used and in the 2023-2024 winter wheat season when dry conditions prevented sampling until over two months after a fertilizer application. Given that ammonification and volatilization happen relatively quickly after ammonium applications, it is not surprising that ammonium-N leaching would peak after fertilization and then drop off.

DRP leaching and plant available DRP were only significantly impacted by season. Brown (2006) reported reductions in soil test phosphorus for all crop rotations over a three-year period, but this reduction was 35-49% greater in double cropped systems than corn alone. Plant available DRP concentrations in this study showed a similar trend but to a lesser degree, with a reduction of 1-16% in winter wheat plots compared to control plots. This smaller percentage in reduction may be explained by the relatively small component that DRP makes up in total soil phosphorus or the shorter time span of this study. Plant available DRP concentrations and DRP leaching also followed a trend of decreasing over time between phosphorus fertilizer applications, which caused both to spike again.

The metrics used to assess nitrogen dynamics in this study and many more have all been used to determine NUE, which does not have a strict definition. While each metric has its own merits, their interpretation is influenced by what information is included and excluded from their calculation (Congreves et al., 2021). This study illustrates how these metrics can be contradictory but provide a sounder understanding of nutrient dynamics, especially when considering levels of nutrients in the soil and environmental losses.

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

The intensification of a corn-soybean rotation with a winter wheat double crop did not significantly increase and even decreased nutrient leaching compared to bare fallow despite the use of fertilizers. Fertilizer timing did not significantly impact yields, but lower fertilizer rates did lead to a yield penalty. NUE as determined by yield-based nitrogen leaching, plant nitrogen uptake, and partial N balances was significantly lower in high fertilizer treatments and greatest in low fertilizer plots. Delayed planting and a potential impediment on BNF due to increased plant available ammonium-N concentrations in the winter wheat plots proceeding soybeans caused a soybean yield penalty. The addition of a cereal rye cover crop in alternate winters further reduced nitrate-N leaching and yield-based nitrogen leaching for the overall crop rotation but also reduced plant available nitrate-N concentrations, which impacted corn and combined cash crop yields. Despite yield penalties following winter wheat double crops and cereal rye cover crops, soybean yields in previously fertilized plots were only slightly lower than county averages and corn yields exceeded county averages. Total yields for the full crop rotations were only significantly diminished in plots that did not include winter wheat. Overall, double cropping increased total crop yields with a neutral to positive impact on water quality and the inclusion of a cover crop in alternate winters further decreased nutrient leaching. The impact of fertilizer rates and timings is greatly influenced by weather conditions, but delayed fertilizer applications were shown to maximize NUE in the winter wheat season when this research occurred. When using delayed fertilization, the grower-recommended rates maximized yields while reduced fertilizer rates resulted in the lowest partial nitrogen balances.

The use of cover crops is an excellent conservation practice for improving soil health and reducing environmental impacts from agriculture, but many farmers may find the costs prohibitive and potential yield penalties concerning. This study shows that double cropping can achieve some of the same goals as cover cropping while providing a profit for the season, which could incentivize farmers that currently do not use cover crops or provide additional income for farmers that do. Using a cover crop in alternate winter seasons further contributes to environmental benefits, and additional crop yields from double crops can make up for any potential yield penalties. Winter wheat yields were significantly reduced by using lower fertilizer rates, but the delayed timing of the medium fertilizer management intensity treatment had higher yields compared to the high treatment that used a fall fertilizer application, which also had the most inefficient nitrogen usage. This implies that delaying fertilization until later in the season is not detrimental and can even be beneficial to yields and can improve NUE while moving some of the winter wheat management away from the busy fall season and into the spring. For farmers concerned with the amount or cost of fertilizer being applied in the winter, lower fertilizer rates can reduce the partial nitrogen balance of double cropped winter wheat while still providing a second annual income.

LIMITATIONS

Seasonal and environmental variability can obscure the influence of treatment effects in short-term field studies such as this study. With only one full crop rotation, data are limited to one repetition of each season or two partial winter wheat seasons due to the start and end dates of sample collections, which can skew results if a season is atypical. The 2023-2024 sampling season, for example, had little precipitation early in the season which prevented samples from being collected and may have masked treatment effects from the fall fertilizer application in high fertilizer plots in the data. The limited establishment of winter wheat in the 2021-2022 season also may not have shown the full impact of fertilizer treatments.

The pan lysimeter sampling method used for leaching data relied on water movement through the soil, which did not provide consistent water samples throughout the collection dates. Water infiltration was limited in dry conditions due to the clay content of the soil, which can contribute to runoff or water being held in upper levels of the soil, and water uptake by plants can also prevent water percolation through the soil. This was especially apparent in late summer and fall, which generally has dry conditions and limited rain in southern Illinois, and sometimes extended into the winter. These dry soil conditions also limited the amount of tension lysimeter samples in certain periods. Loading rates can only be approximated, which can also inflate any biases in the original data.

FUTURE RESEARCH

Continued research into the impacts of double cropping would reduce variability in the results. This could include doing similar research in other regions to determine the effects that different soils and environments may have, repeating this research throughout more years to determine the effects of weather on the fertilizer rates and timings that were used, and using different double and cover crops to determine what rotations can maximize environmental benefits and profits.

This study highlights the importance of directly measuring nutrient leaching until enough data is available to reliably predict nutrient leaching using another metric or model. There is still uncertainty about the effect of various agronomic practices on nitrogen leaching, but even less is understood about phosphorus leaching. More research is needed to determine what factors influence phosphorus leaching and its overall effect on water quality.

The impacts of double cropping on physical soil properties were not addressed in this study, which is an important consideration in the use of cover cropping as a conservation practice. The effect of different tillage practices in double crop seasons would likely influence the physical soil properties and nutrient cycling as well, and determining the effects of crop rotation and tillage on runoff and erosion would provide a better understanding of phosphorus losses as a whole. A cost-benefit analysis that includes fuel usage, fertilizer prices, and total profits would provide clarity beyond yields alone to determine how financially viable double cropping practices are.

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APPENDIX A

EQUATIONS

A.1. Pan lysimeter water sample nutrient concentration to leaching rate conversion.

$$Nitrate - N\ (kg\ ha^{-1})\ leaching = \frac{[Nitrate - N\ (mg\ L^{-1})\ \times\ total\ sample\ volume\ (L)]}{Area\ of\ collection\ pan\ (0.086m^{2})} \times \frac{1}{100}$$

A.2. Crop yield to Mg DW ha^{-1} conversion.

$$Yield\ (Mg\ DW\ ha^{-1}) = \frac{[\left(1 - \frac{Wheat\ moistue\ (\%)}{100}\right) \times Wheat\ wheat\ (lb)]}{Plot\ area\ (300ft^{2})} \times \frac{0.000454\ Mg}{(9.29 \times 10^{-6})\ ha}$$

A.3. Yield-based nitrogen leaching.

$$Yield - based\ nitrogen\ leaching\ (kg\ Mg^{-1}) = \frac{Nitrate - N\ leaching\ (kg\ ha^{-1}) + Ammonium - N\ leaching\ (kg\ ha^{-1})}{Yield\ (Mg\ DW\ ha^{-1})}$$

APPENDIX B

STATISTICAL MODELS

B.1. Code for mixed model with repeated measures used to analyze water quality data in JMP software.

```
Fit Model(
    Y( :Log10NN ),
    Effects( :Rotation, :Fertilizer, :Rotation * :Fertilizer ),
    Random Effects( :Block ),
    NoBounds( 1 ),
    Personality( "Mixed Model" ),
    Subject( :Sample ID ),
    Repeated Effects( :Days Since Planting ),
    Repeated Structure( "AR(1)" ),
    Run(
        Multiple Comparisons(
            Effect( :Fertilizer ),
            Tukey HSD( 1, All Pairwise Differences Connecting Letters( 1 ) )
        ),
        Variogram( AR1( 1 ) )
    ),
    Where( :SeasonYear == "Winter2324" )
);
```

B.2.Code for mixed model with multiple comparisons used to analyze yield and yield-based leaching data in JMP software

```
Fit Model(
	Y( :"Soybean Yield (Mg DW ha)"n ),
	Effects( :Rotation, :Fertilizer, :Rotation * :Fertilizer ),
	Random Effects( :Block ),
	NoBounds( 1 ),
	Personality( "Mixed Model" ),
	Run(
		Repeated Effects Covariance Parameter Estimates( 0 ),
		Multiple Comparisons(
			Effect( :Fertilizer ),
			Tukey HSD( 1, All Pairwise Differences Connecting Letters( 1 ) )
		)
	)
);
```

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Impacts of Intensifying a Corn-Soybean Rotation with Winter Wheat (*Triticum aestivum*) on Nutrient Leaching, Plant Available Nutrients, Crop Yields, and Nitrogen Dynamics in Southern Illinois

Major Professor: Dr. Karl W.J. Williard

Presentations:

Spiers, A.L., Williard, K.W.J., Sadeghpour, A., Schoonover, J.E., Gillespie, J.F., Snyder, J., Vick, A. Impacts of Intensifying a Corn-Soybean Rotation with Winter Wheat on Nitrate Leaching in Southern Illinois. Poster presentation at Illinois NREC Investment Insight, Champaign, IL. February 15, 2024.

Spiers, A.L., Williard, K.W.J., Sadeghpour, A., Schoonover, J.E., Gillespie, J.F., Snyder, J., Vick, A. Impacts of Intensifying a Corn-Soybean Rotation with Winter Wheat on Nitrate Leaching in Southern Illinois. Poster presentation at Outstanding Research Project, Carbondale, IL. February 23, 2024.

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