# NITROGEN MINERALIZATION DYNAMICS OF POST HARVEST CROP RESIDUE IN NO-TILL SYSTEMS

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## Title

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#### **ABSTRACT**

In North Dakota, adoption of conservation tillage practices has resulted in an accumulation of crop residue remaining on the soil surface. North Dakota producers receive a nitrogen credit for long-term no-till but due to previous crop residue this credit may not be realistic for providing partial nutrient needs to subsequent crops in a cool environment with a short growing season. Our objectives were to evaluate the N mineralization potential of common crop residues to determine whether crop residue accumulation in no-till systems can provide sufficient nitrogen quantities needed for subsequent crops. Three lab incubation studies were conducted to provide N mineralization insights for individual crop residues, crop residues over several simulated growing seasons, and crop residue in diversified cropping systems. Differences in soil texture, surface application versus incorporation of residue, freeze and thaw cycles and combinations of residues were all factors examined. Results indicated that crop residue decomposition and N release from the residue treatments generally immobilized N but were not significantly different from the bare soil for nearly all studies. The only exception observed was for the forage radish cover crop which showed the potential to improve soil N mineralization in select three-year rotations. Findings of these studies show that most wide C:N ratio crop residues will immobilize soil N in a no-till system under ideal conditions (i.e. moisture, temperature, and residue particle size). These findings suggestion that a fertilizer N credits may require reevaluation and take into consideration soil moisture with validated data to support the fertilizer N credit.

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#### **DEDICATION**

When it comes to the dedication of this paper, it means a lot because it is my true motivation.

This work and all of my work is to whom who I admire and to whom who I love the most. In fact, my daily journey without remembering him turns to sadness. This person who I am dedicating this work to had a prestigious status back in my home country where many diplomatic people had approached him seeking his advices and his wisdom. He was well known and still is. I always walk in my home country with my head up because of him. My lovely grandfather who passed away 20 years ago, but his reputation is still alive and many times even nowadays his pictures pop up on different social media platforms (Mastour bin Ali). Thank you, my parents (Saeed and Fawzia Alghamdi), for your love, and financial support. Thank you, my wife, for supporting me through my frustration and stressful moments. You are a true cheerleader. Thank you, my brothers and sisters, for believing in me. Thank you, my uncles and aunts, on both sides of my family for your support.

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# LIST OF ABBREVIATIONS

2,4-D	i. n rate.
AMF	i. n rate.
ANOVA Agronomic optimum nitrogen AR Auto-regressive.  C:N Carbon to nitrogen ratio.  CEC Cation exchange capacity.  cm Centimeter.  CO2 Carbon dioxide.  CRP Conservation reserve program CS Compound symmetry.  °C Degrees Celsius.  DON Dissolved organic nitrogen.  EONR Economic optimum nitrogen g Gram.  GLM Generalized linear model.  GLMMIX Generalized linear mixed mo	ı rate.
AR	
C:N	n.
CEC	n.
cm	a.
CO2	ı.
CRP	a.
CS	n.
°C	
DON	
EONR	
g	
GLM	rate.
GLMMIXGeneralized linear mixed mo	
ho	del.
nanectare.	
HELHighly erodible land.	
HSDHonest significant difference	
KPotassium.	
kPaKilopascal.	
kgKilogram.	
LSDLeast significant difference.	

m	.Meter.
Mg	.Megagram.
mg	.Milligram.
mL	.Milliliter.
mm	.Millimeter.
N	.Nitrogen.
N <sub>2</sub>	.Dinitrogen gas.
N <sub>2</sub> O	.Nitrous oxide.
N/A	.Not available.
ND	.North Dakota.
NDAWN	.North Dakota Agricultural Weather Network.
NH <sub>3</sub>	.Ammonia.
NH <sub>4</sub>	.Ammonium.
NH <sub>4</sub> NO <sub>3</sub>	.Ammonium nitrate.
NO <sub>3</sub>	.Nitrate.
No-till	.No-tillage.
NOAA	.National Oceanic and Atmospheric Administration.
NRCS	.Natural Resources Conservation Service.
OM	.Organic matter.
P	.Phosphorus.
PE	.Priming effect.
ppm	.Parts per million.
S	.Sulfur.
SAS	.Statistical analysis system.
SCS	.Soil conservation service.

SES	Soil erosion service.
SOM	Soil organic matter.
SSSA	Soil Science Society of America.
TDR	Time domine reflectometer.
TG	Teragram.
UAN	Urea-ammonium nitrate.
USDA	United State Department of Agriculture.
WWII	World War II

# LIST OF SYMBOLS

%	Percent.
C	Corn.
C-C-C	Corn-corn.
C-S-C	Corn-soybean-corn.
C-SW/R-S/R	Corn-spring wheat/radish-soybean/radish.
F	Flax.
P	Winter pea.
R	Forage radish.
R-R-R	Radish-radish.
S	Soybean.
S-C-S	Soybean-corn-soybean.
S-C-SW	Soybean-corn-spring wheat.
S-SW-S	Soybean-spring wheat-soybean.
S/R-C-SW/R	Soybean/radish-corn-spring wheat/radish.
SW	Spring wheat.
SW-S-C	Spring wheat-soybean-corn.
SW-S-SW	Spring wheat-soybean-spring wheat.
SW/R-S/R-C	Spring wheat/radish-soybean/radish-corn.
WW	Winter wheat.

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#### 1. GENERAL INTRODUCTION

As the world population continues to grow, so has the scale of agricultural production to support the population. To continue to maintain large scale production agricultural demands, soil conservation must be at the center of producers' consideration for land management. A common land management practice commonly found in the U.S. and in the Northern Great Plains of North Dakota is minimum/reduced tillage and no-tillage systems. The Northern Great Plains' producers are aware how intensive agricultural practices can transform their productive land into an environmental catastrophe (i.e. The Dust Bowl of the 1930s). Conversely, less intensive tillage practices coupled with crop residue retention on the soil surface can provide soil health benefits (Baker et al., 2007; Huggins and Reganold, 2008). Thoughtful agronomists today continue to strive for best management practices of the soil for a sustainable future and keep in mind a farmer's economical needs.

North Dakota is a region that experiences extremes in climatic conditions (eg. moisture and temperature), with wet and dry cycles that often shift within a decade, and short growing seasons. Agricultural production has shifted from a monocultural practice of wheat-summer fallow to that with an enhanced diversification and rotation, primarily focused on small grains, but with a major shift to corn and soybean (Kaur et al., 2018; Hansen et al., 2012; Cochran et al., 2006). Soils in the region are rich with a clay soil texture. No-till practices have been widely adopted in the region to conserve soil moisture (Deibert et al.,1986; Unger et al., 1991; Mailapalli et al., 2013). Soil moisture is a significant focus because non-growing season precipitation can account for 30% of overall cumulative precipitation but contributes to 60% of the stored water in the soil (Bauer, 1980; Black and Siddoway, 1980). With a cool climate and no-till management practices, crop residue often accumulates on the soil surface season after

season (Aher et al., 2016). This build-up on top of the soil surface can slow decomposition, tie up nitrate-nitrogen (NO<sub>3</sub>-N) in the soil (immobilization), and delay nitrogen (N) mineralization for subsequent crop needs (Cochran, 1991; Douglas and Rickman, 1992; Stemmer et al., 1999; McConkey et al., 2002). The quantity of nitrogen needed in the soil to facilitate decomposition relies on soil moisture, temperature, oxygen level, and organic matter. In a no-till system, these factors may vary based on crop residue management (i.e.quantity, quality, and thickness) (House et al., 1984; Melillo, 1989; Lipiec and Stepniewski, 1995; Aerts, 1997; Yu et al., 2015).

In addition to improving soil health by increasing soil moisture and soil organic matter in the no-till system, the amount of crop residue combined with a higher C to N ratio of the residues may favor N immobilization from crop residue due to microbial competition with plants for N sources (Allison, 1973; Doran, 1980; Doran, 1987; Havlin et al., 2005). Freeze and thaw cycles may create natural soil disturbance, aid breakdown of residue materials and enable microorganisms to feed on protected decomposing residue, thus enhancing microbial activity (Soulides and Allison, 1961; Ivarson and Sowden, 1970; Ross, 1972). However, it has been observed that the shorter season and cooler climate in the upper Great Plains of North Dakota may impact the N mineralization potential even where a significant amount of total nitrogen is available (Stanford and Smith, 1972).

To satisfy the high N requirements of current high yielding crops, fertilizer N is used to supply mineral needs for optimal yields to replace NO<sub>3</sub>-N no longer adequately mineralized from soil organic matter alone. The goal is to balance soil nutrients, especially NO<sub>3</sub>-N, to meet cropping system needs, and reduce losses to the environment. This requires a more thorough understanding and thoughtful approach to management of crop residue, fertilizer N recommendations, and their interactions.

Despite the benefits of a no-till management practice, studies have reported cases of slowed nitrogen mineralization from crop residue decomposition in a long-term no-till system (McConkey et al., 1996; Kaur et al., 2018). Some have cited carbon: nitrogen (C:N) ratio variability as a notable factor for N availability for use by subsequent crops (Mendham et al., 2004; Muhammad et al., 2011; Kaur et al., 2018). In cooler climates of the U.S., some states have suggested addition of fertilizer N to compensate for microbial activity N requirements to negate or offset N immobilization in long-term no-till systems with heavy accumulation of crop residue (Bundy, 1998; Ketterings et al., 2003; Jokela et al., 2004; Dinkins and Jones, 2019). In North Dakota, questions have been raised about whether current fertilizer N recommendations are adequate for crops with high N needs in long-term no-till systems. Current recommendations in the state are to provide a 34 kg N ha<sup>-1</sup> credit for no-till systems greater than 5 years (Franzen, 2018). However, over the last ten years, fertilizer N recommendations for the state of North Dakota have frequently changed.

The objective of this research is to identify if N contributing to crop fertility needs is mineralizing from a heavy accumulation of crop residue in a no-till system or not. Using long-term incubations studies, this research provides insights to the N mineralization potential and N immobilization patterns observed for common individual crop residues, mixed crop residues, and effects of freeze-thaw cycles on N mineralization from crop residue in diversified cropping systems in the frigid climate of North Dakota. It is hypothesized that N mineralization and/or immobilization for common crop residue treatments in North Dakota are not significantly different from the bare soil itself regardless of soil texture, residue placement, number of freeze and thaw cycles, and time. Instead, patterns observed are more closely related to the observed C:N ratios of the crop residue itself. The purpose of this research is to provide insights to

determine whether the quantity of crop residue remaining on the soil surface in a long-term notill system provides nitrogen to subsequent crops when needed the most to inform future N fertilizer recommendation considerations.

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#### 2. LITERATURE REVIEW

#### 2.1. Abstract

The information that follows provides a detailed review of the literature on conservation agriculture's history and evolution, and addresses challenges in consistent pursuit of best management practices in the U.S. and particularly with observations of an increase in the mass of crop residue remaining on the soil surface. Nitrogen fertilizer recommendations in the region have changed frequently over the last decade for long-term no-till systems. With this, farmers question if nutritional needs are being met in their systems when needed. The northern Great Plains of North Dakota is a heavy agricultural producer; thus, this review is anchored to the region as it progresses. Research on this topic in this region is not new. Much of the literature on the topic began in the mid-twentieth century. Today, the scientific community is asking many of the same questions. Herein, the framework for this research is laid.

### 2.2. History of No-Till Systems

Farming of the land is an ancient practice that can be traced to the Fertile Crescent region along the Tigris, Euphrates, Nile, Indus and Yangtze rivers (modern day Middle East) where wheat, barley, flax, chickpea, lentil, pea, and vetch were commonly harvested (Lowdermilk, 1953; Lal et al., 2007). Over time, farming has evolved from small scale subsistence practices to modern day, large scale agricultural production. Advancement of technology has lead to the development of tillage tools and tractors to meet the demands of a growing human population. Despite a growing global population, the soil is a limited resource that must be conserved and managed to feed the world. Although most soils used for agricultural production across the world are not always the most fertile, civilizations have adapted land cultivation to sustain vegetative growth. Today's agricultural adaptations of crop production mostly rely on some version or

alteration of soil tillage. In order to understand the evolution of tillage practices, it is important to understand the historical context of their application. Modern tillage is a mechanical preparation of the soil for seed germination and an optimal plant growth environment which involves tilling the soil, controlling weeds and pests, capturing water and air for infiltration into the soil, and incorporating crop residue to create a uniform seedbed (Reicosky and Allmaras, 2003).

In contrast, an alternate form of modern crop production is a no-till system where there is minimal soil disturbance by introducing the seed into unplowed/undisturbed soil (Phillips, 1984; SSSA, 2001). An ancient version of a no-till tillage method using human power was recorded around 10,000 years ago where a planting stick was used to place seeds into uncultivated land by the ancient Sumerians (present day Iraq and northern Iran) and other civilizations (Lal et al., 2007). In North America, agrarian practices of the early American Indians relied on manipulation of the soil with simple hand tools and utilized nature itself as a fertilizer (i.e.fish) and natural processes (i.e.slashing and burning) to enhance microbial activity (Phillips, 1984). In Central America and Mexico, no-till practices have been used for centuries whereby seeds are applied to the soil under sunflower residue following a precipitation event (Rolf, 1998).

The U.S. Dust Bowl of the 1930s, a result of prolonged drought and the development of large tractors able to pull large plows and intensive tillage practices throughout the environmentally fragile U.S. and Canadian Great Plains, created unintentional environmental impacts unlike any seen before (Phillips and Young, 1973). Three hundred fifty million tons of soil were carried airborne, from Texas and Oklahoma to New York and the U.S. east coast (Worster, 2004; Lal et al., 2007). Conditions of the Dust Bowl resulted in displacement of over two million people from the Great Plains, environmental impacts, and large economic losses. Environmental impacts of the Dust Bowl included severe soil degradation and erosion, leading to

the failure of crop production. Overall, the severity of this environmental crisis prompted critical changes needed to conserve soils in the United States and the formation of the Soil Erosion Service (SES) agency within the U.S. Department of Agriculture. The SES was later renamed the Soil Conservation Service (SCS) (Worster, 2004).

In the 1940s, technology was evolving and tractors with labor saving equipment helped producers manage larger farms (Lal et al., 2007). Soon after, the first report of a fully no-till system in the U.S. came from North Carolina and Kentucky (Blevins et al., 1971; Phillips, 1984; Rolf, 1998; Lal et al., 2007), though many states including Virginia (Moody et al., 1961), Iowa (Mock and Erbach, 1977), Ohio (Van Doren et al., 1976), and Indiana (Griffith et al., 1988) were early adopters with mixed results of success. Initially, yields under no-till were erratic, but as yields stabilized for producers, the application of the no-till system technique was tested across pastures and crops. Around the same time, plant growth regulators were introduced following World War II, providing producers a method of applying a plant growth hormone (2, 4-D) on their fields to help kill weeds and reduce tillage to reduce the potential of another Dust Bowl. With such products becoming readily available, producers considered shifting focus to reduced tillage practices. The challenges of the no-till equipment evolution was to overcome planting in an undisturbed soil without pushing residues into the soil profile, while also maintaining a proper seeding depth for the crop away from predators and a good moisture environment for germination (Triplett and Dick, 2008). The John Deere "Grassland Drill" openers used by Triplett et al. (1963) is a good example of a tool developed to overcome these challenges. The tool was equipped with knife openers to cut surface residue on untilled soil following the use of a coulter. The design also allowed for fertilizer placement below the seed, avoiding direct contact with the seed.

Reduced and no-till systems have been heavily promoted worldwide to preserve soil from erosion (Ronald and Roy, 2017). A modern-day no-till practice in North America is a permanent non-disturbance of the soil (Rolf, 1998). No-till can reduce the risk of agricultural land degradation through reducing sediment runoff along with fertilizer and pesticide pollution of waterways (Haynes, 1986). It also decreases fuel consumption and labor costs while providing flexibility for planting and harvesting (Phillips, 1984; Haynes, 1986). In a no-till system, crop residue remains on the field post-harvest, reducing the potential for wind and water erosion of the soil while maintaining and providing recycling of nutrients contained in the residue (Baker et al., 2007; Huggins and Reganold, 2008). Other parts of the world have adapted versions of no-till practice where more than fifty percent of land for crop production is managed this way (Baker et al., 2007).

### 2.3. Agricultural Programs following the Dust Bowl

To understand the spread of conservation farming in North America, one must examine the history of agricultural programs and policies. The Dust Bowl of the 1930s was an awakening for American scientific groups and environmental organizations to institute policies to govern and protect the environment, focusing on agricultural practices (McCullough and Weiss, 1985). President Franklin Delano Roosevelt was instrumental in taking a conservationist approach to address current conditions of his time. The dust bowl era, coupled with the great depression forced the country to reflect on not only limits, but also conservationism. A clash of ideals surfaced, eventually leading to economic reform and modification of the United States Department of Agriculture's mission.

The U.S. Department of Agriculture was where conservationism first found a home; however, somewhat contradictory to its commitment to increasing crop production. Initially, they

hired graduates from agricultural colleges and were advocates of using machines, fertilizers, pesticides, and improved seed to get maximum yields. Some land-use planners joined the USDA, calling for a different type of agricultural adjustment than previously laid out (Worster, 2004). Agricultural conservationism was the response which involved safeguarding lands and reviewing traditional property rights where communities might be threatened. Goals were to eliminate intensive farming, preventing erosion through improved practices, rural zoning and regulatory action, resolving farm poverty, and focusing on resource management (Worster, 2004). A portion of the New Deal conservationists were conservation agronomists, examining technique and a form of recovery by manipulation through scientific principles (Worster, 2004). The conservation agronomist pushed for thoughtful management of the land. They implored Americans to go beyond establishing new techniques but encouraged a revolutionary change in the way agriculture was approached (Beeman and Pritchard, 2001). Conservation agronomists have been active in county extension services since 1914, but it was not until the Soil Conservation Service was established that their message began to be amplified (Worster, 2004).

Soon after the Dust Bowl occurred, Congress acted to establish the Soil Conservation

Service (SCS) under the USDA. The SCS pushed for creation of state conservation districts for
local management of land-use regulations. In 1936, the SCS established four promising programs
to prevent soil erosion. The Emergency Erosion Program started in February of 1936 and paid
farmers who wanted to chisel or lister (reduced tillage disturbance) their whole farm for 15 cents
per acre (Bonnifeld, 1979). Another payment program provided many farmers with subsidy of
around seven dollars and farmers were required to apply the conservation practices on their
entire field in order to receive the subsidy. The effort required alternating the planting of crops in
two rows. This was a powerful program for promoting conservation practices; however, this

method was restricted to areas with mild weather conditions (Bonnifeld, 1979). A third program was introduced to eliminate burning off the residue in a field. The SCS opposed this idea because it permanently removed protective cover and would make the soil more vulnerable for soil and water erosion. The last program primarily involved range land management which involved planting grass on government land as well as additional oversight to prevent overgrazing (Bonnifeld, 1979). Overall, the establishment of the SCS was effective in providing restoration of agriculture on the Great Plains. Of the many causes leading up to the Dust Bowl, the SCS was instrumental in responding to (1) the cultivation of lands not ideal for agricultural use, (2) a lack of crop rotation, and (3) capture and release of water in the soil by contour farming or terraces. Even when drought conditions and dust storms returned to the Great Plains in the 1950s, the foundational conservation practices and use of technology introduced by the SCS prevented conditions as severe as those of the 1930s. In 1994, the SCS became the Natural Resources Conservation Service (NRCS) and incorporated conservation efforts to incorporate water, air, energy, and wildlife. This agency and other programs provided for under the congressional Farm Bills have worked to combat the modern and complex agricultural production challenges that are experienced today.

Much of the conservation policy and initiatives that exist today, including U.S. Farm Bill conservation funding, is a result of the conservation policy that was put in place during the Dust Bowl era. Because the land is a non-renewable source, it is important to understand the major degradation of soil erosion, wetland destruction and agricultural runoff (McCullough and Weiss, 1985). Larson et al. (1983) examined nitrogen, phosphorus, and potassium losses from erosion across ten U.S. regions. Research in the northern Great Plains region determined that this region was the second most prone to losses for all nutrients, only behind the U.S. Corn Belt Region. In

response to issues such as this, the 1985 Food Security Act, also known as the 1985 Farm Bill, made large strides to address and counter soil erosion, emphasizing the impact of highly erodible land (HEL) through the Conservation Title (Benbrook, 1988; Gomez, 1995).

Under the program, Highly Erodible Land (HEL), defined as land that has the ability to erode eight times greater than the rate where it maintains its natural formation, was mandated to have an SCS approved management plan. Lands not converted from current cropping systems to conservations reserve programs for a minimum of one year between December 1980 and December 1985 were held to such standards. Compliance required plans to be fully implemented prior to January 1, 1995 (Uri, 1999). During the time, nonpoint source pollution to waterways became evident as a result of the increasing sediments in waterways. These sediments carried soil and nutrients as well as pollutants from HEL. One study concluded, during a period of drought and severe wind erosion events, in the Red River Valley of North Dakota, that wind erosion sediments carried a significant amount of pollutants to surface waterways including nitrogen, phosphorus, potassium, and in some instances, herbicides (Cihacek et al., 1993). The Farm Bill introduced heavier regulatory pressure to encourage land managers to adopt conservation tillage and other practices or suffer consequences of forfeiting supplementary farm program funding. The Farm Bill considered a farmer's eligibility for USDA benefits in relation to their conservation efforts (Uri, 1999). One provision, the Conservation Reserve Program (CRP), focused on reducing soil erosion through removing at risk land from crop production and seeded land into grass (Benbrook, 1988). If the land was to be cropped, some of the approved practices were conservation tillage, crop residue maintaining 30% cover on the soil surface, and crop rotation, as well as combinations of these practices.

The sodbuster program attempted to discourage converting grasslands designated as HEL by increasing focus on conservation compliance and denying federal farm program financial assistance for those that did not comply (Gomez, 1995). Conservation compliance generally involved implementation of some form of conservation tillage or other conservation practice to reduce soil wind and water erosion on cultivated soils. Other efforts to reduce wind and water erosion have included planting windbreaks, grass row barriers, strip cropping, elimination of fall plowing and contour farming. Later, the 1990 Farm Bill expanded the conservation efforts to all land that could result in degradation of water quality. The Natural Resources Inventory of 2003 indicated over 40.5 million hectares of HEL in the U.S.; whereas there were nearly 105 million hectares defined as non-highly erodible. Today, HEL that is annually tilled to produce agricultural commodity crops must be managed under a conservation system for a landowner/manager to qualify for federal agricultural program assistance. The lower limit of conservation tillage and conservation agriculture can be defined as tillage leaving behind at least 30% of the crop residue on the soil surface (Uri, 1999; Tiessen et al., 2010). Reduced and no-till conservation practices aim to leave at least 30% or more crop residue on the soil surface in an effort to reduce wind and water erosion across the soil surface. The 2018 Farm Bill reinforced support for conservationist approaches by producers in the U.S., as well as expanded flexibility of NRCS programs.

# 2.4. Conservation Agriculture in the Northern Great Plains Region

The U.S. Great Plains region exists as a historical formation from sedimentary rocks in the south to glaciated sediments in the north (Brady and Weil, 2010). The region is semi-arid and covers ten states from Canada in the north to Mexico in the south. In North Dakota, precipitation amounts increase from west (300 mm/year) to east (500 mm/year) and potential

evapotranspiration increases from north (3.23 mm/day) to south (3.38 mm/day) (NDAWN, 2020b). Since a large portion of the Great Plains region is subjected to dryland crop production, both precipitation and potential evapotranspiration impact crop production practices (Hansen et al., 2012). The region experiences periodic wet and dry conditions that cycle nearly each decade. Wheat (*Triticum aestivum* L. emend. Thell.) is the traditional crop species grown in the Great Plains region, as it is an optimal wheat environment based on its tolerance of extremes in moisture and temperature. Initially, a wheat-fallow cropping system was established in specific rotations based on the varying needs of southern, central and northern Great Plains region to overcome climate challenges. However, during the fallow period, designed to capture and store rainfall, the soil is periodically tilled to control weeds, thereby destroying protective plant cover and exposing soil to erosion processes. Tillage during fallow aids in water capture and storage, but also causes partial moisture loss due to enhanced water evaporation due to soil disturbance. But, producers in the region have adopted no-till practices to mitigate the risk of soil erosion and improve precipitation storage that comes with extensive fallowing. In addition, the adoption of a no-till practice in the northern region has shifted from a monoculture practice of wheat-summer fallow to continuous cropping and a more diverse crop rotation (Hansen et al., 2012).

Since the Dust Bowl of the 1930s, agricultural practices have shifted towards conservation approaches, although soil erosion continues to be a problem in the northern Great Plains (Cochran et al., 2006). More specifically, the northern Great Plains of the U.S is defined by five states including: Nebraska, Montana, North Dakota, South Dakota, and Wyoming (Liebig et al., 2004). This region leads the U.S. in wheat and beef production and is characterized by large farms and a low population density (Cochran et al., 2006). For context, according to the 2017 Census of Agriculture the average farm in the region was 604 hectares. On the eastern

border of the region, farms are smaller, precipitation is higher, and a greater volume of corn and soybean are grown.

The Homestead Act of 1862 was designed for and responsible for population migration and agricultural cultivation of the northern Great Plains (Cochran et al., 2006). Under the act, each family could claim 160 acres (65 hectares) of land and own all rights to the land after living on it for five years, farming a portion of the land, and improving it (Hurt, 1981). By 1890, most of the land in the region was claimed, although settlements continued through the 1920s. The Homestead Act was terminated due to the 1930s draught. In the 1930s and 40s, as a response to the Dust Bowl, 'stubble mulching', a form of conservation tillage, was introduced in the Great Plains to combat soil erosion (McCalla and Army, 1961). This practice used tillage tools such as the Noble blade and rod weeder that undercut the crop stubble with low soil disturbance destroying weed roots but leaving crop residue on the soil surface. It was used for controlling both water and wind erosion through maintaining crop residue on the soil surface and was developed in Bushland, TX near the heart of the original Dust Bowl (Allmaras et al., 1985). The practice was widely adopted in the western, semiarid areas where a wheat-summer fallow rotation predominated. Although wheat yields were known to vary based on climate, a primary benefit included water conservation due to low soil disturbance and reduced water evaporation (McCalla and Army, 1961). In the semiarid regions of the northern Great Plains, wheat yield was known to increase marginally over fields tilled with a moldboard-plow system, while wheat yield was known to decrease in sub humid portions of the northern Great Plains (McCalla and Army, 1961). The most productive results of stubble-mulching were on wheat and grain sorghum crops grown under dryland conditions (Allmaras et al., 1985).

In the 1940s research was set up at six U.S. based research locations to examine the effects of stubble mulching. From the research, further development of tillage and machinery focused on managing crop residue. The types of machinery used for stubble mulching varied in the Great Plains with primary purposes of either stirring and mixing soil (chisel plows, field cultivators, sweep plows) or cutting beneath the surface without stirring (rodweeders, straight blades, v-sweeps) (Woodruff et al., 1966).

Greb et al. (1970) examined stubble-mulch systems in Colorado, Nebraska, and Montana during summer fallow and determined that additional crop residue from stubble-mulch systems improved water retention and concluded that increased rates of crops residue could result in increased water conservation during wheat production. Similarly, Johnson and Davis (1972) determined that in fields where there was sufficient residue and stubble mulching was implemented, benefits included improved management and mitigation of erosion, improved water conservation, and increased crop yields.

Hansen et al. (2012) examined adoption of no-till practices in the Great Plains and suggested that although stubble-mulching has benefits, a no-till management during fallow may be superior due to increased soil moisture retention promoting early crop growth (Baumhardt et al., 2011). Over the last several decades, no-till management practices have continually increased in the northern Great Plains. The United States Department of Agriculture surveyed land management in twenty-five counties northeast Montana and northwest North Dakota, noting no-till practices on small-grain production. Their findings indicated adoption of no-till practice increasing from 5% in 1989 to approximately 25% in 2004 (Hansen et al., 2012). Not only has no-till become widely adopted in the northern Great Plains, but crop diversification, greater crop

rotation, and greatly reduced fallow periods have been noted in areas where previously only small grains predominated in crop-fallow systems (Cochran et al., 2006).

#### 2.5. North Dakota and No-Till

The thermal environment in North Dakota is cold with 19-year means for annual minimum, maximum and average temperatures of -1°C, 12°C, and 5°C, respectively (NDAWN, 2019). Average precipitation ranges from 356 to 550 mm annually, while snowfall ranges from 635 to 1143 mm annually (NOAA, 2020). Formation of soils in the eastern part of North Dakota are a result of the glacial lacustrine sediments of the ancient lake Agassiz (Thorleifson, 1996). Soils of this region contain smectitic clay which have characteristics of shrinking, swelling, and cracking (Brierley et al., 2011). Moving west, the soils of the state tend to be loamier, as a remnant of the glacial till sediments distributed during the last glacial period. A portion of the state in the southwest has been unglaciated with minerology dating back tens of millions of years with soil development from an accumulation of marine sedimentary deposits. Soils across the region are highly productive, as a result of the clay soil texture and relatively young geologic materials developing under grassland vegetation, thus making North Dakota a top producer of U.S. agricultural products. In North Dakota approximately 89% of the land is used for agriculture and 63% for cropland production (Jantzi, et al., 2019). Conservation tillage accounts of 62.4% of the land management practices (9.9 million hectares), where 16.8% (2.7 million hectares) is managed under no-till systems (CTIC, 2011). The intensity of no-till management practice adoption varies depending on the region of the state.

One of the major attractions to adopting a no-till farming practice in the northern Great Plains has been to conserve soil moisture (Deibert et al.,1986). Cropped fields in North Dakota are generally non-irrigated rain fed fields. An increased amount of crop residue on the soil

surface is known to increase water storage in the soil as a result of the residue acting as an insulator to reflect solar radiation that would typically warm the soil, leading to evaporation of moisture from the soil (Unger et al., 1991; Mailapalli et al., 2013). Thus, no-till serves as a barrier to reduce evaporation. In China, a study examined conventional and no-till treatments to assess impact on soil water storage during the growing season (Liu et al., 2013). Findings indicated the greatest amount of soil water was held during the early growing season in the notill treatment. In North Dakota, water is a factor affecting spring wheat yields in continuous and alternate crop-fallow systems. Because most of the precipitation occurs during the growing season, the water stored in the soil can have an impact on wheat yield. Typically, producers in the western part of North Dakota prefer a no-till system to conserve soil moisture because of the dryer soils combined with a lower precipitation during the growing season, while in the eastern region, soils in the Red River Valley are generally higher in clay, retain more water, and wet (NDAWN, 2020a). The variations in the amount of annual cumulative growing season rainfall is evident from east to west (Figure 1). Soil moisture is significant when considering a no-till practice because in the non-growing season precipitation can account for 30% of overall precipitation in an area but contribute to 60% of stored water in the soil (Bauer, 1980; Black and Siddoway, 1980). Due to the high latitude of the state, the average frost-free growing season is in North Dakota is about 110 days (NOAA, 2020).

Because of the short growing season, adoption of a no-till practice is most often hindered by producers' perception that the residue left on the soil surface will not only increase soil moisture, but it will also slow soil warming and drying in the spring, thus delaying early planting (Larney et al., 1994; Kolberg et al., 1996; Pedersen and Lauer, 2003). Also due to the cooler climate, crop residue tends to accumulate in no-till systems when high residue crops (corn, small

grains) are produced due to a shorter period favorable for residue decomposition. Aher, et al. (2016) evaluated the effect of crop rotation under long-term no-till systems in North Dakota on residue accumulation and observed an accumulation of up to 10 Mg of residue left on the soil surface. Other studies indicate soils with higher amounts of crop residue left on the soil surface might delay plant seedling germination and impact yields, due to lower early season soil temperatures (Griffith et al., 1973; Mock and Erbach, 1977; Dick and Van Doren, 1985).

However, recent research examining soil warming and drying under conservation tillage systems has provided evidence to prove this assumption inaccurate (Alghamdi, 2017). Alghamdi (2017) concluded that any differences in yield may be attributed to fertilizer application methods and rates, but not warming itself. Daigh et al. (2019) has also examined the effects of conservation tillage systems on four full-production scale farms in the Red River Valley of Minnesota and North Dakota finding that producer perceptions do not translate into yield losses.

No-till and other reduced tillage practices have led to improved rain water infiltration into the soil and have promoted crop rotations; however, these practices have led to a greater reliance on fertilizers to replace soil nutrients depleted from the soils a result of some crop rotations and or tillage practice resulting in increasing crop yields due to continuous crop producton (Aase and Pikul, 1995; Peterson et al., 1996; Farahani et al., 1998; McConkey et al., 2002). Conservation tillage practices, such as no-till, also increase the amount of crop residue that remains on the soil, slowing decomposition and subsequent soil N mineralization because of lessened direct contact with the soil mass (Cochran, 1991; Douglas and Rickman, 1992; Stemmer et al., 1999; McConkey et al., 2002). Mineralization is the process by which ammonium N is released into the soil following decomposition of organic matter by microorganisms (Jones and Jacobsen, 2001).

Historically, native soils of the Great Plains developed under grassland vegetation and were fertile with high levels of soil organic matter that when cultivated, were able to supply crops with enough mineral requirements for growth (Cochran et al., 2006). As summer fallow began to be adopted, the high soil organic matter (SOM) resulted in increased soil nitrogen mineralization as a result of soil aeration and increased soil water content due to tillage during the fallow period. As cropping demands and long-term cropping in the region has continued, the demand for soil N availability for plants has also increased but SOM has decreased (Cochran et al., 2006). As a result, N and other fertilizer is now generally used to supply nutrient needs for optimal and adequate yields to replace N no longer adequately mineralized from SOM. In the absence of adequate fertilizer N, immobilization of N can occur on or near the soil surface whereby microorganisms consume N while decomposing the crop residues, converting it to proteins and cell walls for their own development and livelihood, thus removing available N needed for plant growth (Jones and Jacobsen, 2001).

#### 2.6. Nitrogen and its Environmental Impact

The amount of SOM, the rate of soil nitrogen mineralization, rates of fertilizer application, soil texture, and the climate are the components causing environmental concerns about losses of N from agriculture impacting surface and ground water. The adoption of conservation tillage such as reduced till or no-till system changes how water moves through the soil (Shipitalo et al, 2000). Balancing soil nutrients, especially N, is important to meet cropping system needs, while also reducing accumulations and losses to the environment. In an agricultural setting, nitrogen additions to the soil primarily come from three sources: synthetic fertilizers manufactured through the Haber-Bosch process, manure from animals, and nitrogen fixation through legumes (Robertson et al., 2012). The Haber-Bosch process used to manufacture

synthetic nitrogen commercial fertilizer is based on a 3:1 ratio of hydrogen to nitrogen atoms utilizing high temperature and pressure with an iron catalyst to form ammonia (NH3), from natural gas (methane), and air (Haynes, 1986). Worldwide, synthetic N fertilizers are commonly used in the granular form, fluid form, and gaseous form, generally as anhydrous ammonium or urea. The fluid form, urea-ammonium nitrate (UAN), has been widely used in recent years (Robertson et al., 2012). Fertilizer N can be difficult to manage and easily lost to the environment as a result of its many possible complex transformations and cycles (Vos and Van der Putten, 1997; Robertson and Groffman, 2007).

The amount of synthetic nitrogen fertilizers use has increased since World War II. Prior to and during WWII, fertilizer grade N materials were used to manufacture explosives and ammunition. At the end of the war, excess N manufacturing capacity was redirected towards fertilizer manufacturing for agriculture. An 11-fold increase of synthetic nitrogen fertilizer use occurred from 11.6 Tg in 1961 to 126 Tg in 2017 (Mulvaney et al., 2009; Hirel et al., 2011; FAO, 2020). In an agricultural setting, synthetic nitrogen fertilizer has the benefit for increasing crop growth and residue biomass production (Poffenbarger et al., 2017) but excessive amounts of nitrogen can impact water quality. Since nutrients in the no-till systems are known to be concentrated and stratified on the soil surface, the risk of environmental losses via surface and subsurface pathways can be of a concern (Ersahin, 2001). Excessive rates of nitrogen, most commonly in the form of nitrate, delivered to waterways can lead to eutrophication, resulting in hypoxia and anoxia creating dead zones where surface water is discharged (Diaz and Rosenberg, 2008; Seitzinger. 2008; Hirel et al., 2011). Other impacts of nitrogen loading to waterways include drinking water contamination, limitation of water recreation and economic loss to land

managers as a result of decreased efficiencies due to the leaching and run-off losses of applied fertilizer (Randall and Goss, 2008).

Several forms of nitrogen can be lost from the soil depending on their mobility. Since nitrate is a highly mobile form of nitrogen and easily soluble in water, the risk of its leaching into waterways and ground water is of greatest concern versus ammonium which is immobile in the soil (Sharpley et al., 1987). Soil texture also plays a factor in determining the amount of water that can be perculate through the soil under a no-till management system. A field study conducted in Scotland comparing nitrate leaching from sandy soil versus clay soils overlaying a glacial till soil found higher nitrate leaching from sandy soils than from clay soils (Vinten et al., 1993). Sandy soil has a higher infiltration rate than clay soil. In this case, nutrients from no-till under clay soils will be subjected to greater environmental losses than sandy soils under conventional tillage as a result of nutrients stratifying near the top of the soil and susceptible to surface runoff (Haynes, 1986). Nitrate is mobile as a result of its atomic make up, where it holds a negative charge that is repelled by the clay particles that possess a negatively held charge; however, ammonium contains a positive charge that is strongly attracted to the negatives charge of the clay particle and organic matter (Haynes, 1986). Ammonium can be fixed in the clay soil with a 2:1 silica /aluminum ratio; because the ammonium ion diameter fits in the interlayer space of the clay soil mineral. However, ammonium leaching is possible in soils with low cation exchange capacity (CEC) where there is a limited number of cations to hold ammonium at the exchange sites and when potassium is added in a higher ratio than ammonium (Hillel, 1989; Haynes, 1986). However, an aerobic incubation study evaluated the net mineralization of ammonium and nitrate over a wide range of soil orders (Oxisols, Alfisols, Mollisols, and

Histosols) and found that ammonium in soils with a higher CEC (medium to fine texture) was not completely captured in the leachate (Mulvaney et al., 2016).

Dissolved organic nitrogen (DON) and particulate nitrogen are other forms that can be leached, mineralized by microorganisms, or translocated from higher elevations to lower elevations but they are minor contributors to water pollution as compared to nitrate (Jones et al., 2004; Van Kessel et al., 2009; Robertson et al., 2012; Brown et al., 2018). A study was conducted by Izaurralde et al. (1995) examining sources of nitrate leaching from various tillage systems and found that in a no-till system nitrate leaching posed a greater risk to groundwater as compared to conventional tillage. These observed increases under no-till were attributed to the connectivity of macropores in the soil versus the disturbed soil observed under conventional tillage. In an undisturbed soil, macropores develop as result of root development, earthworm and macro fauna activity, freeze/thaw cycles, and wet/dry cycles (Cameron and Haynes, 1986). Macro and micropores have a greater impact on all soil textures because they are routes of major nutrient transport, gas exchange routes and biological enhancement factors. As a result. macropores can be a major source of nitrate leaching to groundwater especially after heavy rainfall events (Shipitalo et al, 2000). For optimizing a no-till system, it is important to understand fertilizer application time, rate, location, and amount to minimize the leaching risk to waterways (Cameron and Haynes, 1986; Shipitalo et al, 2000).

Nitrogen can also be lost to the atmosphere via volatilization, nitrification, and/or denitrification processes. In a no-till system, nitrogen remaining on the soil surface has been known to contribute to greenhouse gases (Cole et al., 1997). Clayey soils have a higher volumetric water content than sandy soils which can lead to denitrification rather than leaching, dependent on the intensity of the rainfall and the season (Cameron and Haynes, 1986). Knowing

that a large part of the nitrous oxide globally comes from agriculture practices (Syakila and Kroeze, 2011; Bhowmik et al, 2016), to reduce its occurrence. Nitrous oxide (N2O) is also a byproduct of nitrifiers in the process of nitrification when synthetic fertilizers are added to the soil in the ammonia form. Nitrous oxide can also be produced by denitrifiers in the process of denitrification when oxygen is limited in the soil and anerobic conditions dominate the status of the soil (Syakila and Kroeze, 2011; Bhowmik et al, 2016). Increased denitrification has been indicated in cropping systems subjected to no-till versus conventional tillage practices (Aulakh et al., 1984). In a no-till system, the accumulation of crop residue left on the soil surface conserves soil moisture and can restricts gas diffusion and reduces oxygen levels in the soil where this practice is applied on heavy soils (i.e.clay soil) or an area subject to flooding; causing nitrate to convert to nitrite, then nitrous oxide or ammonia. Nitrous oxide causes photochemical smog in cities, absorbs the harmful ultraviolet radiation from the sun, and leads to degradation of the ozone layer (Haynes, 1986; Seitzinger, 2008). Ammonia is a very reactive element with water and dinitrogen is an inert gas. However, when released from human activities (i.e.industry and agriculture) can be contributors to air pollution if not managed (Hirel et al., 2011).

The benefit of conservation agriculture is well documented, but if mismanaged can trigger unintentional environmental issues. The addition of nitrogen fertilizers with the adoption of a no-till system can raise environmental concerns for conservationists that observe immobilization of N on the soils surface as an added benefit to mitigate losses to waterways via leaching through the lower profiles. However, nitrogen is an essential nutrient for plant growth because of its involvement in the plant proteins, chlorophyll, and nucleic acids (Haynes, 1986), thus requires availability in the soil profile for plants to uptake for their development and growth. Nitrogen uptake for individual crops varies depending on the type of crop, root depth and yield

goals. The balance between the plants needs and the application of fertilizer is important to protect the environment by leaving a minimum amount of residual nitrogen on the soil after harvest that could potentially be lost to runoff (Vos and Van der Putten, 1997) and leaching through the deeper soil profile. Recommendations for management of nitrogen in the soil should aim to address the concerns of both the farmer and the conservationist. This requires a more thorough understanding of crop residue management techniques, N fertilizer application efficiency, and the interactions for an improved, integrated and holistic approach to management of crop residue.

### 2.7. Management of Nitrogen in the Soil

One method of nutrient management in a field setting is to use catch crops or cover crops. Catch or cover crops can absorb residual nitrogen, sequestering it for use by subsequent crops, contribute to soil organic matter, reduce erosion and compaction, improve the soil microbial community, while also reducing N lost by leaching and runoff (Vos and Van der Putten, 1997; Lord and Mitchell, 1998; Blanco-Canqui et al., 2015; Ruark et al., 2018). Catch crops or winter cover crops are usually grown after harvesting primary row crops to scavenge and capture residual nitrogen in the soil to prevent leaching to groundwater (Al-Kaisi and Licht, 2004; Sainju et al, 2007). Growing catch crops between primary row crops in a wet environment is one way to reduce the risk of nutrient leaching (Sainju et al, 2007). Catch crops can take up residual nitrogen and reduce nitrate leaching to groundwater especially when evaporation is limited and precipitation is high after harvest and before planting new crop (Vos and Van der Putten, 1997). In this instance, this practice can be both beneficial for the farmer and the environment.

Dean and Weil (2009) investigated nitrogen retention for brassica cover crops (forage radish (*Raphanus sativus* L. cv. Daikon), oilseed radish (*Raphanus sativus* L. cv. Adagio), and

rape (*Brassica napus* L.)) as well as rye (*Secale cereale* L.) following soybean as compared to control plots with no cover crop and found cover crop treatments greatly decreased NO<sub>3</sub>-N in the fall, taking up nearly all NO<sub>3</sub>-N from the soil (0-60 cm), therefore keeping NO<sub>3</sub>-N leaching risk at minimum. However, control plot NO<sub>3</sub>-N had a greater risk of NO<sub>3</sub>-N leaching due to NO<sub>3</sub>-N remobilization and downward movement in the soil profile (60-90 cm). In this research, radish utilized NO<sub>3</sub>-N most efficiently, where mineralized N was returned to the soil profile in the spring for subsequent crop use. Rape and rye residue continued to store N in the spring requiring longer term decomposition to release the N. Another study examining non-leguminous cover crops determined that although brassica may have the ability to uptake NO<sub>3</sub>-N and reduce leaching, but not all of the N in the biomass is available/mineralized N that can be used for the following crop when it is needed (Moller and Reents, 2009). A large percentage of the total biomass of radish comes from its roots, thus making it effective for taking up nutrients from the lower soil profile and reducing leaching but could result in reduced mineralization compared to other leguminous cover crops.

Despite cover crops having added benefits for mitigating environmental losses from the viewpoint of the conservationist, several studies have also observed no increase in plant available N to subsequent crops even with the use of cover crops – findings that the farmer should be mindful of, as cover crops may not provide enough nitrogen needed to take an additional N credit for subsequent cropping cycles (Vyn et al., 2000; O'Reilly et al., 2012; Li et al., 2015; Lacey and Armstrong, 2015; Gieske et al., 2016; Hill et al., 2016; Ruark et al., 2018). A recent study in Wisconsin concluded that a radish cover crop did not supply enough N to subsequent corn crop, emphasizing that the assumed cover crop replacement value was not justified for taking a N fertilizer replacement credit (Ruark et al., 2018).

Another way of reducing the environmental degradation through mismanagement of synthetic nitrogen fertilizer is the use of leguminous crops. Leguminous crops require less net energy than cash crops because they scavenge mineral nitrogen from the soil and hold it in their roots, generally requiring less use of nitrogen fertilizers (Hirel et al., 2011), thus a lower cost to the farmer. Leguminous crops have substantial benefits of nitrogen fixation by Rhizobia through symbiotic association versus other agricultural crops which do not have the association (Fustec et al., 2010).

Another nitrogen management technique is the use of nitrification inhibitors to slow down the transformation of ammonium (NH4) to nitrate (NO3). Nitrapyrin is one form of a biological inhibitor which delays by nitrification (*Nitrosomonas* sp.), thereby reducing NO3–N losses through leaching and denitrification. However, results in the upper Great Plains have been mixed (Touchton et al., 1978; Randall et al., 2003; Randall and Vetsch, 2005; Pittelkow et al., 2017; Vetsch et al., 2019). Another means of reducing the fertilizer N release is a polymer coating that is reactive to moisture and temperature in the soil which reduces the risk of leaching and slowly release nutrients to the soil (Robertson and Groffman, 2007). With appropriate management, varying N fertilizer application timing can be an environmental mitigation tool through control measures of increasing ground cover crops and increasing use efficiency. One use efficiency method is where the fertilizer is applied to the crop as a split application. A split application of nitrogen fertilizer can reduce the risk of nitrate leaching/runoff by timing the N available to the crop with the crops nutrient needs as the crop develops in the growth cycle. Many studies have shown the importance of splitting nitrogen application for the crop and the environment (Cameron and Haynes, 1986). A recent field study on wheat was conducted in Ethiopia examining the benefit of varying rates in application of nitrogen fertilizer and at split

application during sowing, tillering, and booting (Belete et al., 2018). A split application of nitrogen was applied at 120, 240, and 360 kg N ha<sup>-1</sup> under five different time-based scenarios. When examining only the application rate, the optimum yield of wheat was achieved at 240 kg N ha<sup>-1</sup> and increased amounts of nitrogen did not result in significant yield differences; thus as nitrogen application increased above the optimum threshold, nitrogen efficiency decreased while nitrogen content in the grain itself increased. Results of the split nitrogen application indicated that optimum wheat yields were achieved when nitrogen was added one-fourth at sowing, onehalf at tillering, and one-fourth at booting at a rate of 240 kg N ha<sup>-1</sup> with added benefits of environmental protection from excess N applications. Randall et al. (2003) studied the timing of nitrogen fertilizer application, with and without a nitrapyrin inhibitor in the fall, spring, and with a split nitrogen application on a clay loam (mollisol) soil with a corn (Zea mays L.) and soybean (Glycine max L.) rotation. Grain yield increased twice as much (+10%) under a split application of fertilizer versus the fall application with nitrapyrin (+5%) and spring application of fertilizer (+5%), when compared to the fall application without nitrapyrin. Overall, greatest economic returns were noted with the spring and split applications of fertilizer in the form of greater grain yield and/or the reduction in expense when nitrpyrin was not used. They further noted the influence of growing season precipitation (May-June) on corn yield, N uptake, and profitability. In years where there was normal to below average growing precipitation, corn yield, N uptake, and profitability were not enhanced with fall application with nitrapyrin or spring applications; however, in years where above-average precipitation was recorded, yield, N uptake, and profitability was greatly enhanced by fall application with nitrapyrin, spring application, or a split application of N.

The form of synthetic fertilizer nitrogen and how it functions has a direct impact on the soil biogeochemical cycles and nitrogen mineralization/immobilization behavior (Reay et. al., 2008; Wang et al., 2014). A study was conducted in China evaluating SOM mineralization and the priming effect (PE) of two different forms of nitrogen fertilizer additions on corn stalks (without leaves). The synthetic forms of nitrogen evaluated were ammonium nitrate (NH<sub>4</sub>NO<sub>3</sub>) and urea. Results indicated significant immobilization of SOM for both fertilizers when the corn residue was not present. However, in the presence of the corn residue, a positive priming effect occurred with SOM, where SOM mineralization occurred more rapidly with the urea application (Wang et al., 2018). In a cooler environment, ammonium nitrate, despite having a lower nitrogen content (26-30%) is more preferred over urea (46%) since urea is relies on a hydrolytic decomposition reaction (Spinelli et al., 2013). Conversely, ammonium nitrate is immediately available to plants; however, can be more easily leached from the soil.

Many studies have attempted to predict nitrogen optimization in the field through method of fertilizer application, timing of fertilizer application, use of cover crops, crop rotation and diversification, and forms of fertilizer. Appropriate soil testing aids in determining the recommended amounts of nitrogen application that may be needed in a field setting.

Management zoning is a one method of representative soil sampling for field scale recommendations executed by collecting samples from similar soil color, yield, electric conductivity, topography, and soil type (Schepers et al., 2004). Even with considerations of organic matter, previous crop type and amount of residue left on the soil surface, it is difficult to measure how much organic matter N can mineralize at each site (Bibi et al., 2016; Sharma and Bali, 2018). It is important to recognize that for the producer, one of the most important ways to control costs and at the same time produce a quality product is through close monitoring and

management of nutrients in the soil. For the conservationist, such management is key to sustaining soil quality and mitigating unintended consequences to other environmental systems. For this reason and as with any other tool, nutrient management techniques require detailed testing and review to ensure that they are operating in the way intended – such as the case with no-till systems and crop residue contribution to enhance soil nutrients.

# 2.8. Nitrogen Mineralization and Immobilization

The microbial decomposition process of crop residue to release N is called mineralization. Organic matter left on the soil surface goes through a microbial process where ammonium (N-NH4) is released into the soil as a product of decomposition (ammonification). When mineral ammonium is released into the soil, an oxidation process occurs by which microorganisms generate nitrate N-NO3 (nitrification). The process of nitrification is assisted by chemoautotrophic bacteria, heterotrophic bacteria, methylotrophic bacteria and chemical oxidation (Haynes, 1986). In order to produce the highest level of nitrification, these bacteria require optimum soil moisture content in the range of -10 kPa to -33 kPa, depending on soil physical characteristics (Miller and Johnson, 1964; Sabey, 1969; Haynes,1986). Maximum N mineralization for microbial activity occurs in the range of 56-60% of water filled pore space (approximately 55% WHC) (Linn and Doran, 1984; De Neve and Hofman, 2002; Wang et al., 2004). The optimum soil temperature for nitrification occurs in the range of 25 °C to 35 °C, depending on the climatic region (Justice and Smith, 1962; Haynes, 1986).

When both mineral forms of N (N-NH<sub>4</sub>, N-NO<sub>3</sub>) are utilized by microorganisms and incorporated into their system, these minerals will not be available to plants (immobilization). Immobilization happens especially when organic matter that is left on the soil has a low nitrogen content (Haynes, 1986). As the organic matter decomposes, carbon is released to the atmosphere

as CO<sub>2</sub> and the nitrogen is recycled to either plants, microbes, or to the soil as humus (Haynes, 1986). The spatial placement of the available nitrogen to either the plant roots or the microbes is a major determining factor of either immobilization or mineralization. Jingguo and Bakken (1996) determined that 3 to 6 mm is the average distance that plant roots can reach available nutrients; whereas those nutrients not captured are subject to immobilization by microbes in the system. One way of measuring crop residue decomposition is through carbon sequestration and carbon dioxide release to the atmosphere and/or from nitrogen mineralization from organic matter decomposition. An inverse relationship between crop residue amounts and decomposition rates has been documented, whereas as the crop residue amount increases, the decomposition rate decreases (Kolberg et al., 1996; Kolberg et al., 1999; Stemmer et al., 1999; Curtin et al., 2000).

When considering crop residue decomposition, temperature is a main factor that effects soil organic matter and nutrient mineralization (Conant et al., 2011). Reported delayed emergence of plants under no-till systems has often been attributed to lower soil temperature due to residue accumulation and thereby slowing seed germination while reducing the ability of microbes to mineralize nutrients from organic matter in the soil, and consequently reducing nitrogen mineralization (Kumar and Goh, 2001). Campbell et al. (1984) conducted a study on the organic matter decomposition rate from eighteen different soils from the Canadian prairie, and some which are also represented in the U.S. Their findings determined that in northern soils where the summer was dry, cool and short, lower decomposition of organic matter was observed versus southern soils where summer was warm, moist and long. In order to maximize benefits of conservation tillage, such as no-till, it is necessary for crop residue to decompose into soil organic matter and inorganic nutrients available to be used for plant growth.

Even though the decomposition of organic materials is slower in the winter, nitrogen mineralization has still been known to occur. A Canadian lab study was conducted with a siltloam glacial till soil to examine extractable N under freeze/thaw cycles varying at low temperatures of 0, -1, -2, -5, and  $-10^{\circ}$ C and controls at  $3^{\circ}$ C (Elliott and Henry, 2009). Extractable N was highest at -10°C with a mid-winter (January) significant freeze/thaw effect where extractable organic N was greater than inorganic extractable N, thought to be a result of the soil proteolytic activity. An incubation study in China, during the non-growing season (late-October to late-April), examined soil nitrogen dynamic effects at subzero temperatures simulating mild freezing (-7 to -2°C), deep freezing (-10°C), and freeze–thaw (-2 to 5°C) with varying plant communities (grassland, shrub, and plantation), finding substantial nitrogen mineralization occurring under freeze/thaw periods (Zhao et al, 2010). During mild-freezing N mineralization stopped and immobilization could still occur; whereas during deep freezing mineralization occurred, but immobilization stopped because of the increased mortality of microbes near the roots releasing nitrogen back to the soil. Stanford and Smith (1972) examined the nitrogen mineralization potential of thirty-nine soils representing Entisols, Alfisols, Aridisols, Ultisols, and Mollisols and indicated that North Dakota, South Dakota, and Minnesota soils displayed a significant amount of total nitrogen but only a small fraction of the nitrogen was mineralizable because of the shorter growing season and cooler climate.

# 2.9. Crop Residue Composition

The relationship between soil carbon (C) and soil nitrogen (N) in crop residue and soils is well documented and is often referred to as the C:N ratio (of soil organic matter). On average, soils have a 10:1 relationship, but the ratio can narrow to 8:1 where soils are well developed and can widen to 18:1 where soils are newly developed (El-Harris et al., 1983; Cochran et al., 1989).

In addition to the enhancement of soil moisture near the soil surface under no-till, an observance of greater organic C and N and thus a higher C:N ratio has been documented on the soil surface favoring residue N immobilization as a result of microbes competing for N energy sources with plants (Allison, 1973; Doran, 1980; Doran, 1987; Havlin et al., 2005). One reason for the immobilization is that as microbes utilize crop residue as an energy food source. When C in the soil is low, soil microbes are limited in food source. Microbes will consume any available N that is in the soil and then release any excess N back to the soil (Vigil and Kissel, 1991; Quemada and Cabrera, 1995). Generally, a crop residue that has a C:N ratio of 25:1 or lower will release nitrogen back to the soil (mineralization) as it is decomposed, while any crop residue that has C:N ratio greater than 25:1 will cause microbes to incorporate the nitrogen (immobilization) in their cell bodies (Cabrera et al., 2005). In addition, a crop residue that has a total N content between 1.5-1.7% generally does not require fertilizer additions, but any crop residue containing less than 1.5% total N, such as wheat straw and corn stalk (0.2-0.6% and 0.7-1.0%, respectively), requires N fertilizer additions (Allison, 1955; Bartholomew, 1965). Generally, fresh legumes contain > 1.5% of total nitrogen in the crop residue versus cereal crop residue which contains less than 1.0% of total nitrogen (Bremer et al., 1991; Schoenau and Campbell, 1996). Not only does the type of the residue have an impact on nitrogen mineralization, but also plant species, plant part, and age of the residue contribute to the amount of nitrogen that can be mineralized and released back to the soil (Haynes, 1986). Aged residue that has been left in the soil over the winter season usually has a narrower C:N ratio than fresh residue which is a product of the same season (Buckman and Brady, 1969; Aher et al, 2016). The fresh residue has a wider C:N ratio that contain soluble components that leach out as the residue is exposed to environmental elements (rain, etc.).

In general, residue left on the soil surface contains organic compounds with contents that vary depending on the organic matter type, species, tissue, and age. Those organic compounds are complex and lignin, protein, hemicellulose, cellulose, water soluble compounds, wax, fats, oils and polyphenol contents are the most common types of compounds (Haynes, 1986). When lignin is found in residue at higher concentrations than the water-soluble compounds, microbial decomposition decreases and the nitrogen retention in the humus increases (Haynes, 1986; Stotzky, 2000; Ruther et al., 2003; Flores et al., 2005; Fang et al., 2007; Xue et al., 2011). However, one might question whether the N increases in the soil are in fact harbored in the humus or the microbial biomass. A polyphenol presence in the organic matter chemical structure slows down the decomposition rate because of it contains an aromatic ring and hydroxyl group which requires extra energy to dissemble (Min et al., 2015). The quality and type of crop residue are important factors that determine decomposition and nitrogen release to the soil (Hatfield and Prueger, 2011; Abbasi et al., 2015). Colvin et al. (1981) and Voorhees et al. (1981) studied crop residue remaining on the soil surface after varying tillage practices and their decomposition from fall to spring. Their findings suggested that the soybean residue decomposed more completely than the cereal crop residues. In southern Brazil, a study examined crop residues of vetch, pea, and wheat (Vicia sativa L., Pisum sativum L., Triticum aestivum L.) and soil type (sandy loam, clay) and quantified the organic decomposition of those residues. In the study, vetch had a narrower C:N ratio (15) due to its higher water-soluble content in the residue than lignin when compared to pea (25) and wheat (51), respectively, and the decomposition of these residues were vetch > pea > wheat (Schmatz, et al. 2017). They concluded that vetch residue decomposed faster due to the higher fraction of water soluble content in combination with higher N content; however, vetch, pea, and wheat residue did not show significant differences in residue

decomposition after 365 days because most of the soluble fraction was leached into the soil with a higher lignin concentration remaining in the residue.

Lignin-to-carbohydrate ratios in crop residues have also been examined to understand potential impacts on decomposition (Johnson et al., 2007). Higher lignin to nitrogen ratios has generally been associated with slowed decomposition of crop residue. A study was conducted by Gezahegn (2016) conducted a lab study examining nitrogen mineralization and the decomposition rate of maize, soybean, and maize/soybean residues collected following harvest. This research documented the direct relationship of C:N ratio and the lignin percent in the residue to the amount of nitrogen released back to the soil. In their study, C:N ratios for the maize, soybean, and maize/soybean residues were measured at 35.3, 12.3, 20.6, respectively, with lignin percentages of 4.3, 2.89, and 3.47 respectively. They concluded that the soybean, with its narrow C:N ratio and least lignin, decomposed faster than maize and maize/soybean residues. The decomposition of lignin-rich crop residue with decreased N contents requires additional N inputs to increase microbial decomposition (Schomberg et al., 1994).

Generally, legume crop residues have narrower C:N ratios than non-legume crop residues. Leguminous crops can fix atmospheric N2 at the root, therefore, at harvest time leguminous crops contain higher nitrogen contents than other cereal/grain crops (Haynes, 1986). A field study was conducted by Kumar and Goh (2001) in New Zealand examining leguminous crop residues (white clover and field pea) versus non-leguminous crop residues (perennial ryegrass and winter wheat) under various tillage treatments (mulch/no-till, ploughed, rotatory hoed, and burned) and nitrogen mineralization and uptake by succeeding winter wheat crop. The study showed that leguminous crop residues provided higher nitrogen mineralization to all treatments than non-leguminous crop residues in the order of white clover >field pea> ryegrass >

winter wheat. Wheat yield reduction in a no-till treatment with non-leguminous crop residues was attributed to the wide C:N ratio and nitrogen immobilization. A field study in the Canadian northern Great Plains examined the effects of a leguminous cover crop (field pea) added to no-till crop rotation (wheat-canola) and subsequent N mineralization. Findings indicated that cover crop residues with their narrow C:N ratio may help offset higher biomass quantity of non-cover crops but did not provide enhanced benefits of N mineralization to the system.

Recommendations suggested that mineralization could be enhanced with additional N inputs (Bedard-Haughn et al., 2013). Janzen et al. (1998) examined impact of soil nutrients in reduced tillage agrosystems in the Canadian northern Great Plains and determined that the loss of SOM by mineralization would require additional N inputs by incorporating legumes, dinitrogen fixers, or fertilizer N into the system. Crop residue practices have variable costs and tradeoffs for the farmer and conservationists. An understanding of the biological cycles and their interaction in a no-till system can enhance and inform best management practices for region- and site-specific N recommendations.

#### 2.10. The Role of Microorganisms

Nitrogen is an essential contributor to the breakdown of organic matter to inorganic measured components through microbial activity. The quantity of nitrogen needed in the soil to facilitate this breakdown is dependent on soil moisture, temperature, aerobicity, and nature of the organic materials, which under a no-till system can vary greatly dependent upon the quantity/thickness of crop residue on the soil surface (House et al., 1984; Melillo, 1989; Lipiec and Stepniewski, 1995; Aerts, 1997; Yu et al., 2015). Microbes are active when they are supplied with optimum moisture, temperature, and oxygen (Vigil et al., 2002). Microbes in the presence of organic matter prefer to obtain their nutrients from the organic matter to satisfy their own

needs and will release excess nutrients into the soil solution. However, nutrients released from organic matter became immobilized as a result of competition between microorganisms rather than being mineralized into the soil solution and available for plants (Haynes, 1986).

Despite no-till systems providing added benefits of increased soil moisture and increased organic matter, they may reduce availability of oxygen from aeration needed by microbes to assist in the breakdown of nitrogen from the crop residue due to the increased moisture. A study was conducted by Vigil and Kissel (1995) in Kansas soils examining the impact of temperature on nitrogen mineralization and residue decomposition. Their findings determined that higher incubation temperatures resulted in increased mineralization and that nitrogen from sorghum and soybean residues mineralized faster at 35°C than 25°C, 15°C, or 5°C, respectively. They concluded that at temperatures lower than 35°C, microbial activity decreased. Another study by Linn and Doran (1984) studied the effects of soil water content on residue decomposition and nitrogen mineralization. They found that aerobic microbes achieved their highest activity when soils were at 60% of soil water filled pore space and that microbial activity was related linearly to organic matter decomposition and nitrogen mineralization.

Enhanced populations of microorganisms have been documented in no-till soils versus those managed under conventional systems (Doran, 1980). As a result, an increase in mineralizable N has been observed at the soil surface of no-till when compared to conventionally tilled fields. In no-till systems the density of arbuscular mycorrhizal fungi (AMF) increases substantially versus other tillage treatments (Hirel et al., 2011). AMF plays a major role in the soil-mineral nitrogen-biological relationship (Jansa et al., 2019) where its role with agriculture crops where it is aiding transport of inorganic nitrogen from the soil solution to plants through the plant roots (Fellbaum et al., 2012; Garcia et al., 2016). AMF is active in the presence of

organic matter, such as residue left on the soil surface, and adding fertilizer nitrogen further stimulates nitrogen mineralization in the system (Jansa et al., 2019). A study was conducted in eastern Canada examining arbuscular mycorrhizal fungi density under conventional tillage, reduced tillage, and no till systems in a maize crop system in sandy loam and clay soils. The study found the density of AMF to be greatest under the no-till system, followed by reduced tillage, and conventional tillage. Lower AMF densities were observed at early stages in the spring as well as in the clay soil at all treatments and observed peak densities during the midgrowing season and later (Kabir et al., 1997).

An incubation study was conducted on a Canadian soil examining factors influencing the stability of microbes in the soil, stating that freeze/thaw cycles had more effects on releasing nutrients and nitrogen back to the soil than wet/dry cycles (Shields et al., 1974). Freeze and thaw cycles enable microorganisms to feed on decomposed residue. The freeze/thaw cycles expand and disturb the soil by breaking up aggregate, exposing protected residue to microbes in the soil (Rovira and Greacen, 1957) and the occurrence of freeze/thaw cycles help releases nutrients back to the soil (Witkamp, 1969) or may breakup residue particles to provide a greater residue surface area. During winter, the native soil organic matter mineralizes through the aid of microbes to release nitrogen (Gasser, 1958). As microorganisms die off, their amino acids and simple sugars are released back to the soil (Soulides and Allison, 1961). During thaw, the surviving microorganism are active and use the surplus cellular material released from the dead microorganisms (Ivarson and Sowden, 1970). Many studies have found an increase in microbial respiration after freeze/thaw cycles, indicating enhanced microbial activity (Soulides and Allison, 1961; Ivarson and Sowden, 1970; Ross, 1972). A lab study was conducted examining microbial activity, carbon respiration and nitrogen mineralization following three freeze/thaw

cycles and found higher CO2 respiration and net nitrogen mineralization after each freeze cycle (Schimel and Clein, 1996). Kolberg et al. (1996) observed a slowing of the organic matter breakdown process during the early establishment of a no-till and reduced tillage environments and recommended an additional application of nitrogen fertilizer during this phase. Kolberg et al. (1999) found greater amounts of residue left on the soil surface from winter wheat, corn, and summer fallow rotation which they attributed to delaying nitrogen mineralization when compared to a winter wheat, summer fallow rotation. Since organic matter in the form of residue contains significant amounts of N, P, and K, it is important to convert them to nutrient available forms for plants (Witt et al., 2000; Rengel and Bowden, 2006).

# 2.11. Nitrogen Dynamics in Long-Term No-till Systems and Knowledge Gaps related to N Cycling in No-Till Systems

Management of nitrogen in the soil is a topic that is complex and continues to be studied. Farmers have relied on fertilizers for primary production, with the most common limiting nutrient heavy nitrogen. At the same time, conservationists are interested in further understanding nitrogen dynamics to eliminate environmental consequences and losses. Nitrogen and plant responses are complex and thus yield projection based on only N availability is difficult to obtain. The benefits of nitrogen fertilization might show up in the plant as better quality and with higher protein content but can also have a negative impact to the environment through greater nitrate leaching (Haynes, 1986). The desire is to create a balance between the costs and benefits.

Nutrient availability and nitrogen mineralization/immobilization from crop residue depends on many factors such as climate, soil texture, sorption and desorption of nutrients loss by the soil, the aeration level of the soil, soil moisture level, land management, crop type, and

crop rotation (Stevens et al., 2005; Andersson et al., 2015; Brown et al, 2018). North Dakota's climatic environment with frigid temperatures (annual mean of 5°C) and short growing seasons (100-135 frost free days), presents unique management challenges. The northern Great Plains has experienced a shift in crop production in recent years. Traditionally, the region produced small grains, sunflower, and barley; whereas in recent years the shift has been towards producing corn and soybean (all of which have wide C:N ratio) (Kaur et al., 2018). In fact, there has been a six-fold increase in average corn (Zea mays L.) yields in the Midwest since the 1930s (Triplett and Dick, 2008) resulting in greater post-harvest biomass as well. With this yield shift and the implementation of conservation tillage practices over the last three decades, a greater volume of crop residue can be found on the soil surface (8-10 Mg ha<sup>-1</sup>). As more crop residue remains on the soil surface, the decreased availability of oxygen due to higher soil moisture as well as lower soil temperature may inhibit residue decomposition and nitrogen mineralization from occurring, thus resulting in reduced yields and requiring more manufactured N for plant growth. For this reason, many earlier studies concluded that an addition of nitrogen fertilizer may be necessary under a no-till system to enhance N availability in the deeper soil profile (Bakermans and deWit, 1970; Bandel et al., 1975; Bandel, 1979). O'Reilly at al. (2012) examined N dynamics of cover crops and the impact of additional of nitrogen fertilizer on catch cropped Canadian prairie fields and determined that for all sites, cover crops were effective in conserving N, but not enough so to provide significant N credits to the following crop rotation. In fact, profit margins (total revenue less cost associated with cover crop for each site) were higher in fields that had N fertilizer additions versus those that did not. Cover crop costs included cost of seed, seed application, fertilizer, and herbicide. A study was conducted in the Canadian prairie evaluating residual nitrogen status from wheat production with varying tillage systems concluded that

nitrogen fertilizer application might be required in the no-till system to enhance nitrogen mineralization (McConkey et al, 2002). Another study was conducted by Clay and Clapp (1990) examining nitrogen mineralization from corn residue collected in the early growing stage (green residue with a narrow C:N ratio of 12) in three different soils with two different fertilizer application rates. Clay and Clapp (1990) found that N fertilizer addition between incubation days 60-120 increased N mineralization from corn residue versus the zero-fertilizer application rate; however, residue mineralization rates for all treatments was similar between the 120-180 day incubation period. Other studies have indicated that an addition of nitrogen fertilizer may result in an N sink as immobilizing N at the soil surface (Doran, 1980).

In 1957, Parker et al. examined nitrogen decomposition from corn residue on the soil surface versus incorporation into the soils and showed a reduced decomposition near the surface. They found that a surface application of low nitrogen residue in the absence of an added nitrogen fertilizer would decrease nitrogen uptake by corn, negatively affecting yield. In the spring, no-till systems are subjected to higher volumetric water holding capacities than other tillage treatments because of the residue on the soil surface. Soils in no-till systems can be prone to water saturation where soil temperatures remain low, thus slowing aerobic microbial activity (Blevins et al., 1984). Under a no-till system, cases of decreased plant nitrogen uptake or availability (immobilization) are reported in other studies (McConkey et al., 1996). McConkey et al. (2002) examined crop growth and soil nitrogen availability under varying tillage systems on the Canadian prairie and concluded lower plant-available N occurred under no-till versus other conservation systems. Lower plant-available N was attributed to lower decomposition and increased N immobilization with recommendations to increase fertilizer-N requirements under no-till for up to 15 years following adaption of no-till. Poffenbarger et al. (2017) conducted a

long-term (16 year) study examining SOC changes for continuous corn and corn-soybean cropping system response to N fertilization rates. They concluded that N fertilization had a direct impact on SOC. As N fertilization rates increased, so did crop residue mineralization and SOC storage up until a certain threshold where maximum yield is achieved based on the agronomic optimum nitrogen rate (AONR). Above this point, higher residual inorganic nitrogen was observed, with no increase in crop residue mineralization. Without N fertilizer inputs, SOC for the continuous corn system declined by two times the rate of that in a corn-soybean system. Kaur et al. (2018) conducted a short lab incubation study examining N and S mineralization from three crop residues (corn, soybean, and spring wheat) for Glyndon and Fargo soils in North Dakota. They observed immobilization of both N and S in residue treated soils over an eight-week incubation period which represented the critical period for corn nutrient uptake. More specifically, residues with high C:N ratios and thus low N resulted in N immobilization in the soil during decomposition – a finding consistent with similar studies (Mendham et al., 2004; Muhammad et al., 2011). A comprehensive review of 2759 paired comparisons of 325 peer reviewed studies examining crop yield under no-till and conventional tillage from 1980-2013 observed that the application of N fertilizer significantly reduced no-till yield declines previously observed in tropical/subtropical and temperate regions (Lundy et al., 2015). While the observations were less pronounced in a temperate region, the reviewed studies reported here only took into consideration fields of non-leguminous crops. This research review calls into question the adequacy of N fertilizer rate recommendations for no-till systems and the prospective yield benefit when applying optimal N fertilizer more specifically in the temperate, northern Great Plains of North Dakota.

In North Dakota, current fertilizer recommendations under a no-till system for producers are to produce a 34 kg N ha<sup>-1</sup> credit for fields, managed under no-till for over five years (Franzen, 2018). However, there is a lack of data to support the recommendation that this credit should be given. But the last decade, N recommendations for North Dakota crops have frequently changed. In 2011, it was concluded that similar yields could be achieved with  $\geq 56$  kg N ha<sup>-1</sup> less in no-till systems when compared to conventionally tilled cropping systems (Franzen et al., 2011). In 2016, the recommendation was revised where a no-till system had been implemented for < five years, an additional of 22 kg N ha<sup>-1</sup> was recommended. For fields under no-till for ≥ five years, the recommendation was to provide a 56 kg N ha<sup>-1</sup> credit for the no-till practice (Franzen et al., 2016). Further revisions were made in 2018 with a five-step process to evaluate management and the recommended N rate by evaluating gross optimal available-N, subtracting soil test nitrate-N, subtracting previous crop credits (for legumes), time under no-till implementation, and soil organic matter content where soils with  $\geq$  five percent organic matter provide 56 kg N ha<sup>-1</sup> credit per each full O.M. percent above five percent. When examining additional research on recommendations for nitrogen credits in other states especially those in the northern part of the U.S., there are recommendations that contradict what is recommended in North Dakota. Numerous studies have reported that no-till systems require a greater N input to achieve a crops best yield potential (Stecker et al., 1995; Bundy, 1998; Ketterings et al., 2003; Jokela et al., 2004; Halvorson et al., 2006; Liu and Wiatrak, 2012). Several states in the northern U.S. with climates similar to North Dakota have recommended additional N fertilizer application in long-term no-till systems. In New York, Ketterings et al. (2003) recommended increasing N fertilizer by 22 kg N ha<sup>-1</sup> as a result of slower soil warming in the spring with increased crop residue. In Vermont, Jokela et al. (2004) evaluate N availability to crops based on soil drainage

and recommended an addition of 34 kg N ha<sup>-1</sup> for no-till corn and a 22 kg N ha<sup>-1</sup> credit for small grains under a no-till system. In Wisconsin, Bundy (1998) recommended increasing N fertilizer by 34 kg N ha<sup>-1</sup> where  $\geq$  50% of crop residue remains on the soil surface, taking into consideration soil texture, SOM, and yield. In Montana, nitrogen recommendations for fields where  $\geq 50\%$  of crop residue remains on the soil surface are based on SOM, soil sampling dates, sampling depth, previous crops, and the amount of residue remaining on the soil surface. The N fertilizer recommendation increases by 17-22 kg N ha<sup>-1</sup> when SOM is < 1% but the same amount of N is given as a credit where SOM > 3%. Where previous crops are legumes, a 11-45 kg N ha<sup>-1</sup> fertilizer credit is recommended, depending on the frequency of the legume grown in the rotation. Increased fertilizer N application is recommended to account for immobilization from stubble left from the previous crop, especially under application methods where N is broadcast (Dinkins and Jones, 2019). In South Dakota, the recommendation for conservation tillage systems such as strip-till and no-till, is to add 37 kg ha<sup>-1</sup> of additional N fertilizer (Clark, 2019). Other studies in Saskatchewan, Canada have indicated that no-till N fertilizer inputs should be greater than inputs under conventional tillage and that those input amounts may vary greatly based on the duration of the system under no-till (McConkey et al., 2002; Lupwayi et al., 2006).

In North Dakota, farmers have questioned if nitrogen is mineralizing from a heavy accumulation of residue or not. Others have extended this question to a review of current fertilizer N recommendations in the state citing necessity of site-specific characteristics in recommendations (Chatterjee et al., 2018). Recommendations become more complex in no-till managed field environments. Aher et al. (2016) and Chatterjee et al. (2016) both demonstrated significant levels of crop residue accumulation in crop rotations in North Dakota. The mineralization of N under frigid temperatures and short growing seasons of the northern Great

Plains, leading to and coupled with heavy residue accumulation, with wide C:N ratios in the residues, have been understudied in the region. Although crop residue contains prospective pools of available N, the quantity of N in the residue can itself be a limiting factor in mineralization. Under current North Dakota recommendations, crops following a soybean (legume) rotation are given a 44 kg N ha<sup>-1</sup> credit when making fertilizer recommendations. However, interaction between the residue of the legume crop mixed with that of corn or wheat is unknown. In 2011, Franzen et al. examined fertilizer responses under no-till and conventional systems for spring wheat fields and concluded that similar yields could be achieved with up to 56 kg N ha<sup>-1</sup> less in no-till culture. This research did not account for stored soil water (soil moisture) differences, difference between tillage systems, or crop (wheat protein) quality in either tillage system to give a fuller picture of adequacy or mineralization of the N. Earlier studies in the region documented the importance in relationship between soil nitrate and soil moisture (Bauer 1965; Reichman et al., 1966; Power, 1967; Young et al., 1967; Power, 1968; Power and Alessi, 1971; Swenson et al., 1979). Reichman et al. (1966) ang Young et al. (1967) indicated a direct correlation between higher available soil moisture and soil N mineralization in relation to yield. Hapka et al. (2000) studied the time and release of nitrogen from six types of North Dakota crop residues including corn (Zea mays L.), potato (Solanum tubersum L.), sugarbeet (Beta vulgaris L.), sunflower (Helianthus annuus L.), canola (Brassica campestris L.), and wheat (Triticum aestivum L.) finding the decomposition rate of sugarbeet and potato at approximately 80% of total mass during the growing season but the decomposition rate of corn, wheat, and canola did not exceed 65% of total mass. When sugarbeet and potato crop residue was present, N availability was greater to subsequent crops and fertilizer application needed were reduced. Conversely, they concluded that the lower decomposition of the other crops may not result in

adequate mineralization for subsequent crop N needs. Aher et al. (2016), at a site near Foreman, North Dakota, found potential residue N deficiencies to compensate for the decomposition of crop for succeeding crops between 56-105 kg N ha<sup>-1</sup> following over winter weathering of the residue and conclude that C:N ratio and mass of residue potentially impacts subsequent crop N needs.

Research in the region has attempted to pinpoint the relationship between rate of N application and crop yield and determined no relationship (Franzen et al., 2016). Franzen et al. (2016) attempted to reexamine field data from previous research (Franzen et al., 2011) producing and examining normalized yield data for two contrasting systems (no-till and conventional tillage) in two environments to support recommended N rates in North Dakota. Data revealed greater available N in the no-till system versus the conventional system; however, did not capture mineralization rates of the available N measured. Again, these studies did not take into consideration soil moisture content, grain quality, and residue biomass. It is known that water is the driving factor for all chemical reactions (Lindsay, 1979) and in the semiarid environment of the northern Great Plains water is a limiting factor for crop production (Wienhold and Halvorsen, 1999), yet recent research in the region has failed to measure such data points. Earlier studies showed that crop yield response and nitrogen fertilizer positively correlated with soil moisture to a depth of 61 cm (Bauer et al., 1967; Cassel, 1970). Bauer et al. (1967) found that maximum crop yield increased congruently with the increase of growing season rainfall (>101 mm), thus enhancing nitrogen mineralization potential.

As shown in Figure 1, regions in North Dakota exhibit climatic variations in rainfall and because of this, standardization of nitrogen recommendations for the full state would seem implausible.

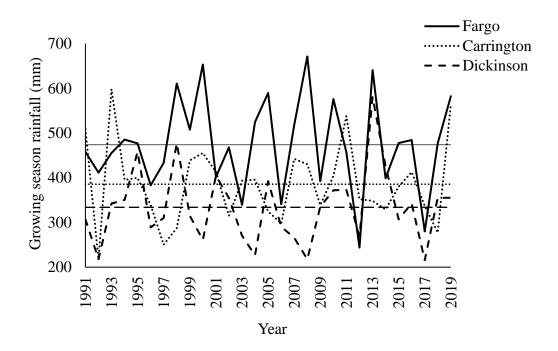


Figure 1. Yearly cumulative growing season (April-October) rainfall (mm) in Fargo, Carrington, and Dickinson, North Dakota, 1991-2019 (NDAWN, 2020a). Horizontal lines indicate the 30-year averages for Fargo, Carrington, and Dickinson independent of one another.

Franzen et al. (2018) presented early study results examining nitrogen non-cycling from cover crops before corn and spring-wheat crops in North Dakota stating that reductions in yield observed in no-till cover crop fields versus no-till non-cover crop fields could be a result of N immobilization (an N-drag) and the subsequent Economic Optimum N Rate (EONR) is reduced. Franzen et al. (2018) further concluded that reductions in yield could not be explained by variances in soil moisture, although soil moisture sampling only occurred at spring planting at the 61cm soil depth. A disregard for soil moisture availability throughout the growing season and depth of soil sampling for nitrate purposes is often an issue in the design of N fertilizer research. This study also did not account for residue biomass and residue C:N ratio returned to the soil. Kahimba et al. (2008) conducted a field study on the Canadian prairie using a cover crop of berseem clover (*Trifolium alexandrium* L.) in oat (*Avena sativa* L.) examining effects on water infiltration, soil temperature, and soil moisture distribution. The study used precise measurement

tools (time domain reflectometer – TDR) to capture soil moisture at various depths (0.2, 0.4, 0.6, and 0.8 m). During spring, no difference in the non-cover crop or cover crop treatment was observed at the surface (0.2 m) but was found to be significantly different deeper (0.8 m) in the soil profile – a nearly 5.5% reduction in soil moisture. Subsequently, during the growing season a significant difference in soil moisture was observed in the cover crop treatment which resulted in significantly lower biomass yields of oat. During mid-August the cover crop treatment had a reduction in soil water contents, of 34.6%, compared to the non-cover crop treatment. A lab incubation study was conducted by De Neve and Hofman (2002) examining a wide range of moisture content water filled pore space (6, 9, 12, 15, 17, 20%) and the rate of nitrogen mineralization from fresh carrot crop residue. Decomposition of the crop residue and the release of nitrogen was found to be more dependent on soil water content than the residue itself. As water filled pore space increased, so did nitrogen mineralization regardless of the presence or absence of the crop residue.

In a no-till system, the amount of nitrogen needed by the soil to break down and use N from crop residue is affected by soil moisture, climatic conditions, aerobic conditions, and organic matter and may vary greatly dependent upon the quantity of crop residue remaining on the soil surface (House et al., 1984; Melillo, 1989; Lipiec and Stepniewski, 1995; Aerts, 1997; Yu et al., 2015). In a no-till system, a greater C:N ratio has been documented at and near the soil surface and subsequent N immobilization has been observed where microbes compete for N energy sources (Allison, 1973; Doran, 1980; Doran, 1987; Havlin et al., 2005). Parker et al. (1957) noted a reduced decomposition of corn residue near the soil surface versus an incorporation into the soil.

Recent development research on this topic is still lacking in North Dakota. With a range of conservation tillage practices widely adopted across the region, it becomes important for farmers to have a better understanding of complimentary N fertilizer best management practices to achieve better yield and/or cost-benefit strategies.

Despite the costs of fertilizer inputs, many farmers are willing to modify N credits when calculating fertilizer needs for optimal system and plant productivity. Many are also cautious and attempt to reduce any possibility of N loss to environment. Both parties lack the data needed to support the recommendation for current N credits in North Dakota. The under-application of N fertilizer can be impactful to the farmer's wallet (yield) and the over-utilization of N fertilizer can have negative impacts on the environment and farmers profit, and cause a headache for the conservationist. The profitability of N fertilizer application is apparent when soil N mineralization can be accounted for and N fertilizer is attributed as the main source of available N to crops (Mulvaney et al., 2006; Dourado-Neto et al., 2010; Mulvaney et al., 2016). There is a current lack of understanding of the decomposition of crop residues laying on the soil surface of no-till fields in North Dakota, where the N comes from for decomposition of that residue. The difficulty of measuring N released from the decomposing residue on the surface and its fate in partitioning to the soil (or loss to volatilization as greenhouse gas) and its contribution to direct pathways between microbes and plants is still not clear in most research studies. Further research is needed to provide the data needed to support fertilizer recommendations for no-till systems in North Dakota to maximize both economic return and minimize environmental risk. Stanford and Smith (1972) suggested long-term incubation studies to aid in estimation of nitrogen mineralization potential. The following research reported aims to leverage similar methods in a long-term incubation study to measure N mineralization potential for individual crop residues

most common in the region, determine if the quantity and quality of crop residues is contributing to or offsetting N immobilization observed, and evaluate the influence of climatic conditions on crop residue decomposition.

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## 3. CROP RESIDUE CONTRIBUTION TO SOIL N MINERALIZATION AND IMMOBILIZATION IN NO-TILL CROP FIELDS IN NORTH DAKOTA

## 3.1. Abstract

Variable wet and dry precipitation cycles in North Dakota have encouraged producers to adopt conservation tillage practices to capture moisture in dry years. As a result, an accumulation of crop residue has been observed. Current recommendations in North Dakota encourage a fertilizer nitrogen (N) credit where long-term (> 5 years) no-till systems are used. Producers are concerned that the increased N-rich crop residue is not supplying N needs to subsequent crops when needed during the growing season. Soils of the region have been documented to have an amount of nitrogen, though only a portion may be mineralizable in the soil. This study aims to examine whether nitrogen is mineralizing from common crop residue and in prevalent soil series of the region using long-term incubation studies. The Fargo, Forman, and Heimdal-Emrick soil series were selected for their wide representation in soil characteristics. Seven residue treatments with different C:N ratios were selected to include corn (Zea mays L.), soybean (Glycine max L.), flax (Linum usitatissimum L.), forage radish (Raphanus sativus L.), winter pea (Pisum sativum L.), spring wheat (Triticum aestivum L.), and winter wheat (Triticum aestivum L.), plus one control. The C:N ratios for the crop residue treatments were: corn (73), soybean (53), flax (77), forage radish (8), winter pea (18), spring wheat (76), and winter wheat (101). Biweekly leachings were conducted for nine incubation periods and the leachate were collected and analyzed for NO<sub>3</sub>-N. Soil with higher organic matter (i.e., Fargo) often resulted in higher N mineralization [Fargo (1.63 mg NO<sub>3</sub>-N kg<sup>-1</sup>) > Forman (0.65 mg NO<sub>3</sub>-N kg<sup>-1</sup>) > Heimdal-Emrick (0.38 mg NO<sub>3</sub>-N kg<sup>-1</sup>)]. Forage radish and winter pea crop residues, with narrow C:N ratios, were the only treatments showing N mineralization potential over the bare, unamended soil. Other crop residue

treatments with wide C:N ratios demonstrated immobilization of N when compared with the soil itself.

## 3.2. Introduction

Over 11 million hectares of cropland reside in the state of North Dakota, a top U.S. producer of wheat, spring wheat, soybeans, corn, and forage crops (USDA, 2018). Soils of the region are primarily Mollisols, characterized by a high level of soil organic matter and nutrient content. Stanford and Smith (1972) examined the nitrogen (N) mineralization potentials of soils and concluded that Mollisols in North Dakota, South Dakota, and Minnesota demonstrated significant amounts of N in the soil, although a small fraction of it is mineralizable. In the state of North Dakota, approximately 5.7 million hectares of cropland is managed under a no-till or conservation tillage management practices (USDA, 2015). Conservation tillage is widely known for building soil health and increasing soil organic matter as a result of increased remaining crop residue on the soil surface and low soil disturbance. In long-term no-till systems, accumulation of up to 8 to 10 Mg/ha of residue have been observed (Aher et al., 2016). Due to the region's frigid climate, residue decomposition and nutrient mineralization from these residues can be limited by a short frost-free period of 100-135 days (NOAA, 2020). These factors pose the question of whether adequate N is mineralized from accumulated residue to be available for use by subsequent cropping systems, or if additional N fertilizer is needed to compensate for the high residue accumulation. Crop residue remaining on the soil surface has a decreased rate of decomposition as a result of a lower soil temperature near the surface as well as reduced contact of residue particles with a favorable microbial decomposition environment. This impedes or slows the residue decomposition and nitrogen mineralization process which can cause yield reduction in some cases. Earlier studies examining this same topic have concluded that in a notill system, effective nitrogen fertilizer management strategies are critical and additions may be required to compensate for nitrogen supply shortage deeper in the soil profile (Bakermans and deWit, 1970; Bandel et al., 1975; Bandel, 1979). In the soil, balancing nutrients, especially N, is important to meet a crops system needs, while also reducing N accumulations that can be lost to the environment.

In long term no-till systems, an accumulation of aged residue remains on the soil surface. Hapka et al. (2000) conducted a study examining the timing and release of nitrogen from six types of North Dakota crop residues including corn (Zea mays L.), potato (Solanum tubersum L.), sugarbeet (Beta vulgaris L.), sunflower (Helianthus annuus L.), canola (Brassica campestris L.), and wheat (Triticum aestivum L.). Their research determined that the decomposition rate of sugarbeet and potato were approximately 80% of total mass, while the decomposition rate of corn, wheat, and canola mass did not exceed 65% throughout the growing season. These findings validated N availability to subsequent crops when sugarbeet and potato crop residue was present, thus reducing fertilizer application needs only after sugarbeet and potato crop residues remained in the field. However, the low decomposition rate for the other crops may not result in adequate N mineralization to reduce subsequent crop N needed from fertilizers. Kaur et al. (2018) examined N and S mineralization from three crop residues (corn, soybean, and spring wheat) on Glyndon and Fargo soils from the Red River Valley of the North and concluded the occurrence of immobilization in residue treated soils over an eight-week incubation period. The absence of a reliable natural nitrogen source is a concern as crops cannot rely on nutrient availability from crop residues alone, especially where short growing seasons are present.

In North Dakota, the short growing season may inhibit the available time necessary for nitrogen mineralization and decomposition to occur when certain crop residue is present

especially during critical nutrient demand during the early to mid-growing season. By understanding the decomposition and N release of common crop residues in ND, producers can better determine nutrient fertilizer management strategies. Currently in North Dakota, producers are recommended to take a 44 kg N ha<sup>-1</sup> credit under a long-term no-till system (i.e.6 or more years) (Franzen, 2018). However, research into nitrogen requirements in conservation tillage or no-till systems with heavy crop residue is scant, though in North Dakota there have been many revisions to these recommendations. Franzen et al. (2011) examined wheat yields from conventional and no-till systems, concluding that similar yields could be achieved with a  $\geq$  56 kg N ha<sup>-1</sup> reduction in no-till systems over conventionally tilled systems. However, in 2016, this recommendation was revised to take into consideration the length of time a field had been under no-till implementation (Franzen et al., 2016). Further revisions were made in 2018 to integrate a more systematic approach to take into consideration gross optimal available-N, soil test nitrate-N, previous crop residue type, time under no-till implementation, and soil organic matter (Franzen et al., 2018). Several states in the northern U.S. have recommended that N should be added in long-term no till systems when heavy crop residues are present (Bundy, 1998; Ketterings et al., 2003; Jokela et al., 2004; Clark, 2019; Pariera-Dinkins and Jones, 2019).

Currently, N management recommendations do not take into consideration temporal residue decomposition and N mineralization and immobilization effects of varying crop residues, but instead cite standardized recommendations. The decomposition rate of different crop residues is directly affected by multiple factors, two of them being the quality and the type of residue (Johnson et al., 2007; Aher et al., 2016; Chatterjee et al., 2016). The C:N ratio is one measurement that has been utilized to determine decomposition of crop residue. Previous research (Li et al., 2013; Lynch et al., 2016) determined that a narrow C:N ratio improves residue

decomposition and nitrogen mineralization, useful for subsequent crop growth, as compared to other crop residues with a wide C:N ratio. A study by Aher et al. (2016) looked at the C:N ratio in both fresh and aged crop residue, finding a narrower C:N ratio in the aged residue, due to higher carbon in fresh residue.

Residue decomposition is accomplished by microbes when they are supplied with optimum moisture, temperature, and oxygen (Vigil et al., 2002). In the soil, microbes compete with plants for their source of nutrients; whereby microbes aim to satisfy their own needs first and then release excess nutrients into the soil for plant uptake. As a result, immobilization occurs when nutrients are being utilized by microbes versus being available to plants (Haynes, 1986). A loss of soil organic matter in reduced tillage systems has been documented in the Canadian Northern Great Plains resulting in recommendations for increased nitrogen inputs through use of crop species (i.e.legumes, dinitrogen fixers) and/or fertilizer nitrogen (Janzen et al., 1998). Also, it has been observed that water is the limiting factor for all chemical reactions (Lindsay, 1979). This is particularly a concern in the semiarid environments where water is limited when plants need it most during the growth stage. Nutrients move through the water to the plant root in processes called mass flow and diffusion; and when water is deficient, can lead to nutrient deficiency in plants. The northern Great Plains experiences wet and dry precipitation cycles and water is a limiting factor for crop yield, as well as nutrient mineralization (Wienhold and Halvorsen, 1999). However, research in the region has failed to measure such data points over time and at various depths in the soil to determine when nitrogen is mineralizing and available to subsequent crops.

Economics and environmental considerations driving precise nutrient application to crops requiring nutrient application adjustments based on actual crop needs. Standardized

recommendations are useful in warmer and more moist climates which allow for optimum and more consistent N mineralization from crop residue. However, in cooler climates with highly variable precipitation, the rate of residue decomposition is less predictable, resulting in less certain N mineralization. This brings to question if changes are necessary in N management for no-till production in the cooler climates of the northern Great Plains. Research in the region has not yet validated nitrogen availability of specific crop residues, which is essential to determine if producer fertilizer application needs are being met. There are a variety of crops grown in North Dakota; many of them are grown under conservation tillage or no-till conditions. To examine nitrogen mineralization potential, Stanford and Smith (1972) suggested long-term incubation studies. The goal of this research is 1) to measure N mineralization potential for individual crop residues common in North Dakota and 2) to evaluate N mineralization potential within the common soil series of the region, both using long-term incubation studies. Findings of these incubation studies will help determine plant available N within North Dakota no-till fields.

### 3.3. Materials and Methods

## 3.3.1 Experimental Design

A laboratory study using a randomized complete block design with three replicates was set up using three soils and seven residue treatments, plus an untreated soil control for each soil. The three soils were from the Fargo (Fine, smectitic, frigid Typic Epiaquerts) (Soil Survey Staff, 2016), Forman (Fine-loamy, mixed, superactive, frigid Calcic Argiudolls) (Soil Survey Staff, 1998a), and Heimdal (course-loamy, mixed, superactive, frigid Calcic Hapludolls) (Soil Survey Staff, 1998b)-Emrick (Course-loamy, mixed, superactive, frigid Pachic Hapludolls) (Soil Survey Staff, 2014) soil series. Each soil series contained three replicates of seven residue treatments, plus one untreated control (n=24 total samples for each soil). The seven residue treatments were:

corn (Zea mays L.) (C), soybean (Glycine max L.) (S), flax (Linum usitatissimum L.) (F), forage radish (Raphanus sativus L.) (R), winter pea (Pisum sativum L.) (P), spring wheat (Triticum aestivum L.) (SW), and winter wheat (Triticum aestivum L.) (WW). The C:N ratios for the crop residue treatments were: corn (73), soybean (53), flax (77), forage radish (8), winter pea (18), spring wheat (76), and winter wheat (101). Fresh residue was collected immediately in the fall following harvest and analyzed for its chemical composition using an Elementar Vario Max® CN analyzer during a previous study conducted by Aher, et al. (2016) in 2011 and 2012. Upon collection, residue was oven dried at 60°C and ground in a Wiley mill to pass a < 2 mm screen. The Fargo soil series sample was collected near the NDAWN weather station in Fargo, North Dakota (46° 53'47" N 96°48'42" W). The Forman soil series samples was collected at the Conservation Cropping System Project (Aher, et al., 2016) near Forman, North Dakota (97°) 38'38" N 46°05'05" W). The Heimdal-Emrick soil series sample was collected at the Carrington Research Extension Center near Carrington, North Dakota (46° 53'34" N 102°48'46" W). Bulk soil samples were air dried, crushed, and sieved through a 2 mm screen. Residue treatment samples (n=63) were prepared containing 15 g of soil mixed with 15 g of quartz sand (20 mesh), to facilitate leaching and enhance aeration in the sample, and 0.50 g of residue. The purpose for having 0.5 g of residue is to mimic crop residue accumulation in conservation tillage. In this study 0.5 g of crop residue is equivalent to 6.25 Mg/ha in a field setting.

> Surface area of leaching tube =  $\pi r^2 = 8.04$  cm<sup>2</sup> or 0.0008 m<sup>2</sup> 0.5 g crop residue / 0.0008 m<sup>2</sup> = 625 g/m<sup>2</sup> or 6.25 Mg/ha

Controls (n=9) contained 15 g of soil mixed with 15 g of sand only. Samples were then transferred to labeled glass leaching tubes kept in a controlled-environment constant temperature room at 22°C with moisture at 80% saturation and were incubated as described by Stanford and

Smith (1972). The controlled temperature simulated soil temperatures that may be expected under field conditions with a crop residue cover in North Dakota (NDAWN, 2020). Before the mixed samples were transferred to the leaching tubes, a small amount of glass wool was placed in the bottom of the leaching tubes to prevent soil sediment loss during leaching. After the mixed soil samples were transferred to the leaching tubes, glass wool was also placed at the top of the leaching tubes to prevent soil disturbance during leaching solution application. The soils were characterized for salinity (EC), organic matter (OM), plant available nitrogen (N), phosphorus (P), and potassium (K) by the North Dakota State University soil testing laboratory (Table 1) using standard NCERA-13 methods (Nathan and Gelderman, 2015).

Table 1. Initial soil characteristics for nitrate (NO<sub>3</sub>-N), phosphorus (P), potassium (K), pH, electric conductivity (EC) and organic matter (OM) for Fargo, Forman, and Heimdal-Emrick soil series.

Bon Berres.											
	Soil Characteristics										
Soil Series	$NO_3-N$	P	K	pН	EC	OM	Sand	Silt	Clay		
	(kg/ha)	(ppm)	(ppm)		(mmhos/cm)	(%)	(%)	(%)	(%)		
Fargo	20	17	530	7.6	0.77	6.2	6.4	37.6	56		
Forman	11	15	250	7.6	0.43	5.1	33.6	31.4	35		
Heimdal-	91	17	410	5.8	0.34	4.4	37	39	24		
Emrick											

Soil textural analysis was conducted using the hydrometer method (Bouyoucos, 1962). An initial leaching of the samples was done using 50 mL of 0.01M CaCl<sub>2</sub> was added to the glass tubes in 10 mL increments followed by 10 mL of nutrient solution described by Stanford and Smith (1972) to remove ambient levels of NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup>N. Subsequently, biweekly leaching of the incubations (n=10) were conducted at 2, 4, 6, 8, 10, 12, 14, 16, 18, and 20 weeks. Following leaching, Parafilm® was used to cover leachate test tubes to prevent contamination and to preserve soil water content during this study. Air vents were created in the parafilm to allow for soil respiration. Leachate was covered, collected and refrigerated (8-24 hours) if

necessary, until mineral N (NO<sub>3</sub>-N and NH<sub>4</sub>-N) analysis was conducted using a Timberline TL 2900 NH<sub>4</sub>/NO<sub>3</sub> analyzer (Timberline Instruments Inc., Boulder, CO).

Following the final incubation (20 weeks, n=10 total readings), soil pH for all incubated samples (n=72) plus 3 pre-incubation control samples of each soil was determined using a Beckman Coulter 340 pH meter. The pH variation was due to the decomposition effects of the crop residue in the sample.

# 3.3.2. Statistical Analysis

A repeated measures Analysis of Variance (ANOVA) model was used to determine the effect of crop residue treatment, soil texture, incubation period, and their interactions on nitrate and ammonium mineralization with SAS Generalized linear mixed model (GLIMMIX) procedure. As the measurements of nitrate and ammonium mineralization are collected from same experimental tube unit repeatedly over incubation period, certain covariance structure would be imposed on the error term of the model to address the correlation among the measurements. Akaike's Information Criteria (AIC) was used to determine the appropriate covariance structure and the smaller AIC value the better. Throughout this study, AR(1) covariance structure was always producing smaller AIC value. LS-mean of each level of crop residue treatment for each soil type was estimated and pair-wised multiple comparison was performed with Tukey's Honest Significant Difference (HSD) test with an alpha level of 0.5. Similarly, LS-mean of each level of crop residue treatment within each incubation period for each soil type was estimated and Tukey's (HSD) test with an alpha level of 0.05 was used to find the LS-means that are significantly different from each other.

The One-way ANOVA model was also used to investigate the effect of crop residue treatment on soil pH for each soil texture. In this analysis, the comparisons between control and

other levels of crop residue treatment were interested, therefore, Dunnett's test was used as it was designed control the familywise type I error rate at or below 0.05 when multiple comparisons of treatment group with control are performed. All analyses were conducted by SAS version 9.4 (SAS Institute, 2013).

### 3.4. Results and Discussion

Overall mean soil NO<sub>3</sub>-N mineralization capacity for crop residue treatments varies with soil texture from 1.15 mg NO<sub>3</sub>-N kg<sup>-1</sup> to 5.8 mg NO<sub>3</sub>-N kg<sup>-1</sup> (Table 3). For all soil series, the control (bare, unamended soil) means showed net N mineralization varying from 0.66 mg NO<sub>3</sub>-N kg<sup>-1</sup> to 2.95 mg NO<sub>3</sub>-N kg<sup>-1</sup>. When comparing the three soil series and nitrogen mineralization over time, the Fargo soil series displays the highest NO<sub>3</sub>-N overall mineralization means among the three soils over the nine incubation periods [Fargo (1.63 mg NO<sub>3</sub>-N kg<sup>-1</sup>) > Forman (0.65 mg NO<sub>3</sub>-N kg<sup>-1</sup>) > Heimdal-Emrick (0.38 mg NO<sub>3</sub>-N kg<sup>-1</sup>)] (Figure 2). This is due to the high OM evident in the Fargo soil series (Table 1). When higher organic matter is present, the potential for mineralization to occur is also higher (Follett, 2008).

Nitrogen mineralization varies based on crop residue treatment and the C:N ratio of the material. Forage radish (C:N=8) NO<sub>3</sub>-N mineralization mean in the nine incubation periods is significantly higher when compared to each crop residue treatment in nearly all soil series (Table 2). Forage radish is the only treatment that shows an overall net mineralization in all soil series over the control. Pea (C:N=18) shows slight mineralization for all soil series, although significantly different from the forage radish with the exception of the Forman soil series. Corn (C:N=73), flax (C:N=77), soybean (C:N=53), spring wheat (C:N=76), and winter wheat (C:N=101) (Aher, et al. 2016) show a net immobilization and are often similar regardless of soil series, and significantly different from the forage radish and pea treatments. The reason for the

differences between forage radish and pea as compared to corn, flax, soybean, spring wheat, and winter wheat is the narrow C:N ratio in forage radish and pea (C:N < 25) and they are green and growing at the end of the growing season while the other residues are senescent.

Higher mineralization occurs in the narrow C:N ratio crops earlier in the incubation series (i.e.growing season) as compared to the later incubation series (i.e.end of the growing season). For example, forage radish mineralization rates peaks between Day 42 and Day 56, while the wider C:N (C:N > 25) ratio crops reach their peak mineralization between Day 98 and Day 112, but still immobilizing (Figure 3, 4, 5). Pea is the only other crop that exhibits mineralization over the control early in the incubation series. At Day 98 a spike in spring wheat NO<sub>3</sub>-N mineralization is observed for the Fargo soil series. A possible explanation for this is a natural microbial shift that occurs later in the growing season in the high OM environment of this soil.

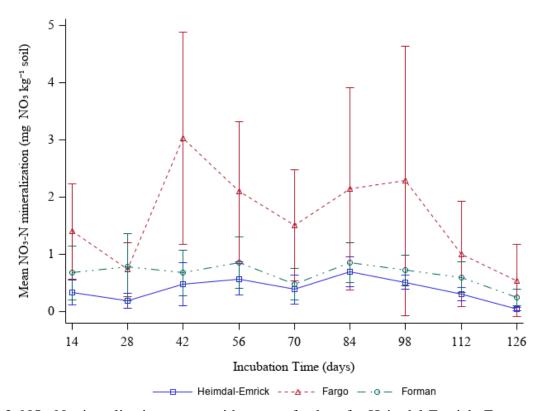


Figure 2. NO<sub>3</sub>-N mineralization means with range of values for Heimdal-Emrick, Fargo, and Forman soil series over nine incubation periods, regardless of crop residue treatment.

An evaluation of the effects of specific crop residues on soil pH are shown in Table 2. Mean soil pH varied from 5.6 to 6.0 for the Heimdal-Emrick soil series, from 6.7 to 6.9 for the Fargo soil series, and from 6.2 to 6.6 for the Forman soil series. Heimdal-Emrick is the only soil series that shows significant differences in the soil pH where the radish is the only crop residue treatment significantly different from the others. This is likely due to its lower buffering ability because of its coarser texture.

Table 2. Past incubation mean soil pH by soil type for crop residue type treatment.

Crop Residue Treatment	Soil pH					
	Heimdal-Emrick	Fargo	Forman			
Soil only	$5.7b \pm 0.27$	$6.8a \pm 0.10$	$6.2a \pm 0.08$			
Corn	$5.6b \pm 0.04$	$6.7a \pm 0.06$	$6.3a \pm 0.08$			
Flax	$5.6b \pm 0.04$	$6.8a \pm 0.07$	$6.3a \pm 0.07$			
Pea	$5.8b \pm 0.04$	$6.8a \pm 0.12$	$6.4a \pm 0.02$			
Radish	$6.0a \pm 0.06$	$6.7a \pm 0.10$	$6.6a \pm 0.02$			
Soybean	$5.8b \pm 0.06$	$6.9a \pm 0.02$	$6.4a \pm 0.06$			
Spring Wheat	$5.8b \pm 0.15$	$6.8a \pm 0.09$	$6.4a \pm 0.10$			
Winter Wheat	$5.6b \pm 0.09$	$6.8a \pm 0.10$	$6.4a \pm 0.18$			

†Different letters within a column are significantly different at the 0.05 level using Dunette's multiple comparison test.

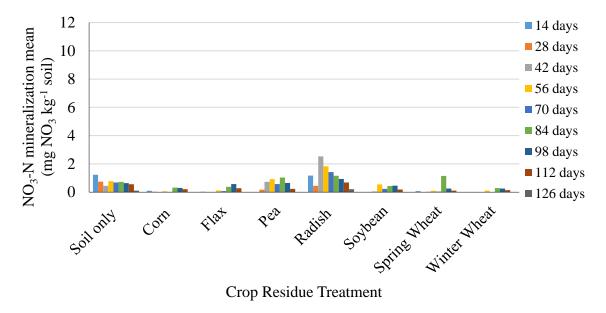


Figure 3. Mean NO<sub>3</sub>-N mineralization patterns over time for soil control, corn, flax, pea, radish, soybean, spring wheat, and winter wheat crop residue treatment for the Heimdal-Emrick soil series.

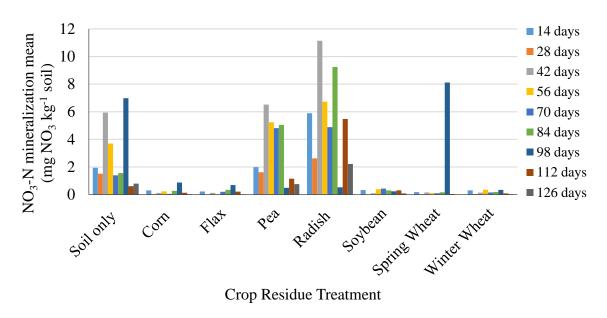


Figure 4. Mean NO<sub>3</sub>-N mineralization patterns over time for soil control, corn, flax, pea, radish, soybean, spring wheat, and winter wheat crop residue treatment for the Fargo soil series.

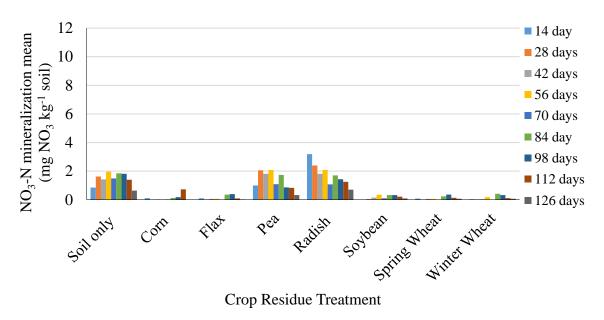


Figure 5. Mean NO<sub>3</sub>-N mineralization patterns over time for soil control, corn, flax, pea, radish, soybean, spring wheat, and winter wheat crop residue treatment for the Forman soil series.

### 3.4.1. Cumulative Mineralized NO<sub>3</sub>-N

Over eighteen weeks of lab incubation, there are noticeable differences in the cumulative mineralization per soil texture for the Heimdal-Emrick, Fargo, and Forman soil series (Table 3).

The greater cumulative mineralization for the Fargo soil series could be due to its texture, soil pH, water holding capacity, and organic matter (6.2%). For the Fargo and Forman soils, both cover crops (radish and pea) showed net mineralization when compared to the control. However, for the Heimdal-Emrick soil, radish is the only cover crop that shows cumulative mineralization greater than the untreated control.

### 3.4.2. Mineralization/Immobilization of NO<sub>3</sub>-N

Figures 6, 7, and 8 helps to exhibit each specific incubation period of leaching to determine whether mineralization or immobilization is occurring according to the associated days. The residue NO<sub>3</sub>-N mineralization is compared to the unamended soil which is represented by the zero line and is used as a baseline. Value above the zero line indicates N mineralization, while below the zero line suggests N immobilization. Mineralization and immobilization amounts varied based on soil texture as shown in the following three figures.

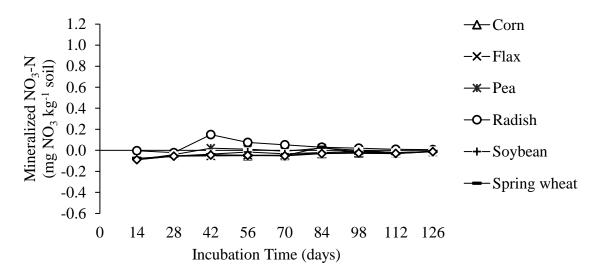


Figure 6. Mineralization/immobilization of NO<sub>3</sub>-N for the Heimdal-Emrick soil series over nine incubation periods. The horizontal X-axis line represents soil mineralization and the residue N mineralization is shown relative to soil mineralization.

Table 3. Mean and cumulative NO<sub>3</sub>-N mineralization for nine incubation periods and overall mean for corn, flax, pea, radish, soybean, spring wheat, and winter wheat crop residues for Heimdal-Emrick, Fargo, and Forman soil series in North Dakota.

		Nitrogen	mineraliza	ation per le	aching inc	ubation per	riod (days)	, mg NO <sub>3</sub> k	g-1			
Soil	Crop Residue	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	5 <sup>th</sup>	6 <sup>th</sup>	$7^{\mathrm{th}}$	8 <sup>th</sup>	9 <sup>th</sup>	Cumulative	Overall Mean <sup>±</sup>
Series	Treatment	(14 d.)	(28 d.)	(42 d.)	(56 d.)	(70 d.)	(84 d.)	(98 d.)	(112 d.)	(126 d.)		
Heimdal-	Soil only	$1.228a^{\dagger}$	0.738a	0.444b	0.778b	0.686ab	0.734a	0.636ab	0.556a	0.107b	5.907b	$0.656b \pm 0.35$
Emrick	Corn	0.092b	0.030b	0.000b	0.060b	0.021b	0.326a	0.299b	0.212a	0.000c	1.040d	$0.115d \pm 0.14$
	Flax	0.027b	0.000b	0.000b	0.119b	0.079b	0.384a	0.572ab	0.275a	0.000c	1.456d	$0.16cd \pm 0.22$
	Pea	0.006b	0.178b	0.734b	0.926ab	0.573ab	1.037a	0.655ab	0.237a	0.000c	4.345bc	$0.48bc \pm 0.42$
	Radish	1.171a	0.452ab	2.535a	1.827a	1.421a	1.155a	0.933a	0.687a	0.209a	10.389a	$1.154a \pm 0.88$
	Soybean	0.000b	0.020b	0.051b	0.547b	0.238ab	0.437a	0.458ab	0.193a	0.004c	1.946c	$0.216c \pm 0.24$
	Spring Wheat	0.073b	0.001b	0.025b	0.102b	0.035b	1.150a	0.251b	0.108a	0.000c	1.745c	$0.193c \pm 0.53$
	Winter Wheat	0.000b	0.004b	0.000b	0.111b	0.002b	0.288a	0.255b	0.137a	0.000c	0.797d	$0.088d \pm 0.12$
Fargo	Soil only	1.942b	1.513ab	5.931a	3.702ab	1.394ab	1.551a	6.976a	0.607b	0.792b	24.408b	$2.952b \pm 3.37$
-	Corn	0.308b	0.021b	0.116b	0.230b	0.053b	0.272a	0.868a	0.124b	0.021b	2.013c	$0.249c \pm 0.46$
	Flax	0.224b	0.001b	0.114b	0.020b	0.193b	0.334a	0.690a	0.213b	0.013b	1.801c	$0.223c \pm 0.35$
	Pea	1.987b	1.608ab	6.520a	5.244a	4.810a	5.047a	0.490a	1.150b	0.750b	27.606ab	$3.36ab \pm 2.68$
	Radish	5.894a	2.618a	11.144a	6.721a	4.877a	9.245a	0.522a	5.473a	2.213a	48.706a	$5.811a \pm 4.49$
	Soybean	0.321b	0.009b	0.100b	0.381b	0.430b	0.301a	0.232a	0.301b	0.080b	2.154c	$0.259c \pm 0.19$
	Spring Wheat	0.176b	0.022b	0.152b	0.096b	0.096b	0.163a	8.119a	0.030b	0.000b	8.854bc	$1.11bc \pm 4.59$
	Winter Wheat	0.323b	0.032b	0.144b	0.347b	0.157b	0.189a	0.342a	0.086b	0.026b	1.625c	$0.200c \pm 0.19$
Forman	Soil only	0.852b	1.621a	1.425ab	1.964a	1.493a	1.847a	1.816a	1.396a	12.690a	12.690a	$1.552a \pm 0.56$
	Corn	0.109b	0.000a	0.019b	0.005b	0.022b	0.123b	0.182c	0.725ab	1.209b	1.209b	$0.148b \pm 0.25$
	Flax	0.097b	0.024a	0.055b	0.069b	0.000b	0.358b	0.398c	0.091b	1.149b	1.149b	$0.136b \pm 0.16$
	Pea	0.998b	2.059a	1.818a	2.076a	1.088a	1.739a	0.864bc	0.832ab	11.738a	11.738a	$1.434a \pm 1.03$
	Radish	3.189a	2.391a	1.810a	2.084a	1.045a	1.703a	1.433ab	1.257ab	18.484a	18.484a	$1.868a \pm 1.16$
	Soybean	0.000b	0.042a	0.148b	0.346b	0.102b	0.323b	0.330c	0.215ab	1.606b	1.606b	$0.188b \pm 0.18$
	Spring Wheat	0.081b	0.009a	0.062b	0.060b	0.000b	0.236b	0.358c	0.130ab	0.937b	0.937b	$0.117b \pm 0.13$
<del>+</del>	Winter Wheat	0.031b	0.026a	0.035b	0.175b	0.000b	0.420b	0.320c	0.110b	1.117b	1.117b	$0.140b \pm 0.21$

<sup>†</sup>Different letters within a column in each soil series are significantly different at the 0.05 level using Tukey's HSD test. 
<sup>±</sup> Nitrogen mineralization mean over all incubation periods for each crop residue within individual soil series.

Forage radish was the only treatment that showed an overall net mineralization of NO<sub>3</sub>-N in all soil series over the bare soil. Corn, flax, soybean, spring wheat, and winter wheat showed a net N immobilization in all soil series. Pea (legume) NO<sub>3</sub>-N mineralization was slightly higher or near the mineralization rate of the untreated soil controls.

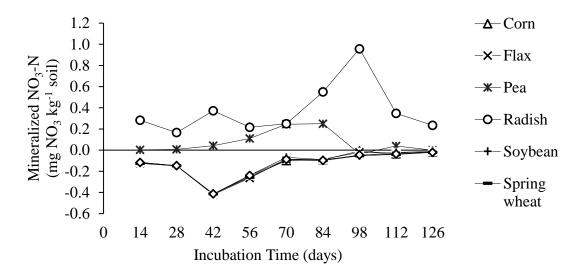


Figure 7. Mineralization/immobilization of NO<sub>3</sub>-N for the Fargo soil series over nine incubation periods. The horizontal X-axis line represents soil mineralization and the residue N mineralization is shown relative to soil mineralization.

### 3.5. Conclusion

An observation of immobilization of NO<sub>3</sub>-N from non-leguminous crop residues is consistently observed in our results. Kaur et al. (2018) observed similar results using North Dakota soils. Mineralization of the low C:N cover crops (radish and pea) was also shown to occur in the earlier incubation periods as compared to other crop residue treatments. Other studies, including those with similar soils and northern region of the U.S., have concluded that despite cover crops providing NO<sub>3</sub>-N benefits, the benefits may not be an adequate substitution to fertilizer application and that nitrogen mineralization from crop residue alone may not be enough to award a credit for the following crop season (Vyn et al., 2000; O'Reilly et al., 2012; Li

et al., 2015; Lacey and Armstrong, 2015; Gieske et al., 2016; Hill et al., 2016; Ruark et al., 2018).

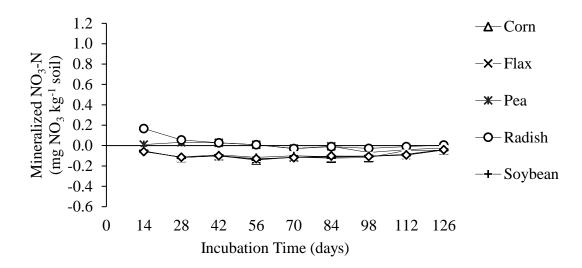


Figure 8. Mineralization/immobilization of NO<sub>3</sub>-N for the Forman soil series over nine incubation periods. The horizontal X-axis line represents soil mineralization and the residue N mineralization is shown relative to soil mineralization.

Given the extreme in temperatures in the region and the wide variation in conditions across the state from east to west, further studies should aim to integrate climate conditions (ie. freeze and thaw) and the potential impact of water on mineralization and immobilization trends. In this study, crop residue was incorporated into the soil to speed up mineralization. Further studies should include a surface application of crop residue to more closely simulate the field conditions of the no-till system. Based on our results alone, additional N fertilizer may be needed in fields where the crop residue shows immobilization trends. However, additions of NO<sub>3</sub>-N can accelerate C mineralization in residue and suppress mineralization of C in soil organic matter (SOM), narrowing the C:N ratio to improve residue decomposition and nitrogen mineralization (Mahal et al., 2019).

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# 4. TYPE AND QUANTITY OF CROP RESIDUE AND FREEZE-THAW CONTRIBUTION TO SOIL N MINERALIZATION IN NO-TILL SYSTEMS

#### 4.1. Abstract

The adoption of no-till management practices has increased in the United States over the last decade. In the state of North Dakota, approximately 5.7 million hectares of cropland is managed under no-till or conservation tillage management practices. Even though conservation tillage is known for building soil health, increasing soil organic matter, capturing soil moisture, and reducing wind and water erosion; it also presents unique best management practices as a result of the increased mass of crop residue that remains on the soil surface. Farmers in North Dakota are concerned whether plant needs are being met from nitrogen fertilizer that is currently being applied based on current North Dakota recommendations for long term no-till systems. The previous study (Chapter 3) indicated immobilization trends for non-leguminous crop residues from three different soil textures common in the region under a simulated conventional tillage condition. A Forman clay loam soil (fine-loamy, mixed, superactive, frigid Calcic Argindolls) was used in this study as it is one of the most representative soils in the region. This study examines whether N mineralization from a crop residue applied to the soil surface would result in similar or varying results when compared to crop residue mixed into the soil while also evaluating freeze-thaw contribution to soil N mineralization. Six residue treatments with different C:N ratios were selected for this study and include: corn (Zea mays L.), soybean (Glycine max L.), forage radish (Raphanus sativus L.), winter pea (Pisum sativum L.), spring wheat (Triticum aestivum L.), and winter wheat (Triticum aestivum L.). Biweekly leachings of a nutrient solution were conducted for six incubation periods with a three-week freeze period between each cycle at 0°C. Analysis of the NO<sub>3</sub>-N following each incubation cycle showed that

crop residues with a narrow C:N ratio contributed to greater instances of N mineralization during every incubation cycle and that accumulation of crop residues with a wide C:N ratio over each incubation cycle following the first incubation did not offset the immobilization trends observed in the first incubation. Freeze-thaw cycles might have a positive effect on N mineralization trends or this may indicates a shift in the microbial population for crop residues with a narrow C:N ratio as indicated in the last two simulated growing seasons of this study.

## 4.2. Introduction

In a no-till agricultural system, crop residue remains on the soil surface whereby a drier environment with lower soil temperatures may slow and/or reduce nitrogen mineralization, thus affecting crop yields. In areas where there is a short growing season, no-till practices have been perceived by producers as slowing planting and crop emergence as a result of delayed soil warming and drying (Larney et al., 1994; Kolberg et al., 1996; Pedersen and Lauer, 2003; Licht and Al-Kaisi, 2005). In a frigid environment these concerns are more pronounced because in notill systems the crop residue that tends to accumulate when high residue crops (corn, small grains) are left on the soil surface. Alghamdi (2017) examined soil warming and drying in a frigid environment for corn-soybean systems and provided evidence to suggest that these perceived delays are not related to moisture and temperature of the soil. Daigh et al. (2019) have also reported research on full-production scale farms in the Red River Valley of Minnesota and North Dakota (i.e. frigid environment) finding that producer perceptions of delayed warming and drying of the soil do not translate into yield losses. This begs the question of where these perceived losses are coming from. In research by Alghamdi (2017), any differences observed in yield were attributed to fertilizer application methods and rates. Many earlier studies concluded that an addition of nitrogen fertilizer may be necessary under a no-till system to increase N in the

deeper soil profile (Bakermans and deWit, 1970; Bandel et al., 1975; Bandel, 1979), yet modern recommendations often overlook these decades of research.

The rate of soil N mineralization is dependent upon crop residue factors that include, but are not limited to, the type and quantity of residue and other soil factors; one being temperature (Miller and Geisseler, 2018). As residue continues to accumulate on the soil surface in a no-till system, it is necessary to examine if enough N is being provided to subsequent crops to offset the potential immobilization in the system. Schoenau and Campbell (1996) stated that conservation tillage such as reduced and no-till systems will result in greater surface accumulation of crop residue on top of the soil surface in which it will slow residue decomposition of wide C:N ratio crops. No-till systems provide added benefits of increased soil moisture and organic matter, although they may reduce availability of oxygen from aeration that is needed by microbes to assist in the breakdown of nitrogen from the crop residue. In addition to increasing soil moisture, no-till systems can be susceptible to water saturation as a result of increased crop residue on the soil surface. Thus, the activity of microbes may be reduced along with soil shading and slower soil drying due to cooler temperatures (Blevins et al., 1984).

Green and Blackmer (1995) examined the rate of nitrogen fertilization and its effect on residue decomposition on corn-corn and corn-soybean fields in the Corn Belt and determined that nitrogen immobilization tended to decrease with increase nitrogen fertilization as a result of the nitrogen fertilizer adding N to the total residue biomass. Increasing rates of nitrogen fertilization decreased the time required for nitrogen mineralization to occur. This process was expedited when soybean residue was the proceeding crop as a result of the nature of the plant material. Li et al. (2013) found that nitrogen mineralization occurred more quickly with crop residue placed on the soil surface versus crop residues incorporated into the soil. Satchell (1974)

defined the decomposition process as a biological process where plant tissues are broken down by microorganisms. Microorganisms can break down residue more quickly when plant residue is incorporated with the soil (Stemmer et al., 1999) as compared to remaining on the soil surface (Vanhie et al., 2015). Coppens et al. (2007) found that incorporated crop residues decomposed faster than leaving residue on the soil surface and that higher nitrogen fluxes were more pronounced with crop residue incorporation. For the residue that did remain on the soil surface, the absence of moisture was a greater limitation to decomposition than N itself.

To aid in the breakdown of high lignin content crop residue, such as corn, many producers apply liquid N to their fields after harvest. Al-Kaisi et al. (2017) examined corn residue decomposition and the application rate of liquid urea ammonium nitrate (UAN) following harvest concluding that increased rates of decomposition were not attributed directly to the application rates of N, but instead a result of increased air and soil temperature. They expanded their conclusions to mention that limiting of liquid N application with less than ideal air temperature conditions and/or limited availability of soil moisture during critical periods of residue decomposition phases was desirable. Additional studies have determined similar finding where decomposition effects were attributed to temperature and moisture availability (Al-Kaisi and Guzman, 2013; Reis et al., 2011; and Kirschbaum, 1994).

In cooler climates of the Northern Great Plains, such as in North Dakota, highly variable precipitation and temperature conditions during crucial periods of crop N needs can result in the rate of residue decomposition being less predictable, resulting in less certain N mineralization for crop needs. Vigil and Kissel (1995) examined the impact of temperature on nitrogen mineralization and residue decomposition in Kansas soils. Their findings indicated that higher incubation temperatures resulted in increased mineralization. At temperatures lower than 35°C,

microbial activity decreased. Nitrogen from sorghum and soybean residues mineralized faster at 35°C than 25°C, 15°C, and 5°C, respectively. Aher, et al. (2016) examined C:N ratios and the mass of residue on the soil surface near Forman, ND and indicated potential N deficiencies to succeeding crops ranging from 56-105 kg N ha<sup>-1</sup> following winter weathering of the crop residue. The region has a frigid climate where residue decomposition and nutrient mineralization from crop residues can be limited by the short frost-free period of 100-135 days (NOAA, 2017; Carter, 1994).

In the Canadian prairie, an incubation study was conducted to examine the factors influencing the stability of microbes in the soil (Shields et al., 1974). Results indicated that freezing and thawing cycles had a great effect on releasing nutrients and nitrogen back to the soil when compared with wetting and drying cycles. The reason for this was that the freeze and thaw cycles enabled microorganisms to feed on decomposed residue. During freezing and thawing, the soil is expanded and disturbed exposing the residue to microbes that helps release nutrients back to the soil (Rovira and Greacen, 1957; Witkamp, 1969) or may breakup residue particles to provide a greater residue surface area. During the winter, native organic matter of the soil mineralizes to release nitrogen (Gasser, 1958) resulting in some microorganisms dying off and their amino acids and simple sugars being released back to the soil (Soulides and Allison, 1961). During thaw periods, surviving microorganism are active and feed on the nutrients released from dead microorganisms (Ivarson and Sowden, 1970). As a result, many studies have noted the increase in microbial respiration following freezing and thawing cycles (Soulides and Allison, 1961; Ivarson and Sowden, 1970; Ross, 1972; Schimel and Clein, 1996).

Current recommendations for N management in North Dakota do not regard temporal residue decomposition and N mineralization and immobilization effects that vary with different

types of crop residue in their recommendations. Instead, standardized recommendations are cited for long-term no-till systems (i.e. managed for six or more years) where producers are to take a 34 kg N ha<sup>-1</sup> credit (Franzen, 2018). But over the last ten years, recommendations have varied for the state of North Dakota. However, research data to support this recommendation is still lacking. Standardized N recommendations are useful in warmer and moister climates which allow for optimum N mineralization from crop residue. Management recommendations for nitrogen fertilization of soil should aim to address concerns of the producer and advance best management practices. The objectives of this study are twofold: 1.) evaluate if the type and quantity of crop residue is offsetting the N immobilization and 2.) evaluate the influence of freezing and thawing on crop residue decomposition.

### 4.3. Materials and Methods

# 4.3.1. Experimental Design

A laboratory study using a randomized complete block design with three replicates was set up using one soil and six residue treatments, plus an untreated soil control (n=21). The soil was a Forman (Fine-loamy, mixed, superactive, frigid Calcic Argiudolls) soil series (Soil Survey Staff, 1999). This soil was selected as it is similar to most common soil series in glaciated parts of the region. The six residue treatments were: corn (C), soybean (S), forage radish (R), pea (P), spring wheat (SW), and winter wheat (WW). Fresh individual crop residue was collected immediately in the fall following harvest and analyzed for its chemical composition using an Elementar Vario Max® CN analyzer during a previous study conducted by Aher, et al. (2016) in 2011 and 2012. Upon collection, residue was oven dried at 60°C and ground in a Wiley mill to pass a < 2 mm screen. Bulk Forman soil was collected at the Conservation Cropping System Project (Aher, et al., 2016) near Forman, North Dakota (97°38'38" N 46°05'05" W). The bulk

soil sample was air dried, crushed, and sieved through a 2 mm screen. Residue treatmentsamples (n=18) were prepared containing 15 g of soil mixed with 15 g of quartz sand (20 mesh) to facilitate leaching with 0.50 g of residue placed on the soil surface. The amount of crop residue left on the soil surface is equivalent to 6.25 Mg/ha in a field setting and its calculation is shown in the previous chapter (Chapter 3). This procedure followed that of Stanford and Smith (1972). Controls (n=3) contained 15 g of soil mixed with 15 g of sand only. Samples were then transferred to labeled glass leaching tubes where soil was placed into the tube and crop residue was then placed on top of the soil surface to simulate no-till residue accumulation. This experiment is different from the experiment in the previous chapter in that it simulated no-till residue accumulation on the soil surface rather than being incorporated into the soil/sand mixture. Leaching tubes were kept in a constant temperature room at 22°C simulating the average temperature in the region during the growing season over the last thirty years. Those tubes were incubated as described by Stanford and Smith (1972). Before the soil samples were transferred to the leaching tubes, a small amount of glass wool was placed in the bottom of the leaching tubes to prevent soil sediment loss during leaching and was placed at the top to prevent soil and residue disturbance during leaching solution application.

Five incubation periods and four freeze/thaw cycles were conducted for the experiment. Each cycle represented an annual growing season. Between each cycle, there was a three-week freeze period to represent an annual freeze/thaw cycle. Following each leaching cycle (n=5), an additional portion of 0.5 g of individual crop residue was placed on the soil surface (total=2.5 g per leaching tube, over the course of the study). Biweekly leachings of the incubations were conducted at 2, 4, 6, 8, and 10 weeks for the first cycle. For cycle two, an additional leaching was conducted at 12 weeks. For cycles three, four, and five, additional leachings were conducted

at 12 and 14 weeks to observe the possibility of cumulative effects. For the first leaching of the samples and due to the dry nature of the soil/sand/residue column, 50 mL of 0.01M CaCl<sub>2</sub> was added to the glass tubes in 10 mL increments followed by 10 mL of nutrient solution as described by Stanford and Smith (1972) to remove ambient levels of NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N. Subsequent leachings used 30 mL of 0.01M CaCl<sub>2</sub> and 10 mL nutrient solution. Following each leaching, Parafilm® was used to cover the incubation tubes to prevent contamination and to preserve soil water content during this study. Air vents were created in the parafilm to allow for soil respiration. Leachate was collected, covered and refrigerated (8-24 hours) if necessary, until mineral N (NO<sub>3</sub>-N and NH<sub>4</sub>-N) analysis was conducted using a Timberline TL 2900 NH<sub>4</sub>/NO<sub>3</sub> analyzer (Timberline Instruments Inc., Boulder, CO). At the end of an incubation period, the leaching tubes were then transferred into the freezer for three weeks at 0°C.

## **4.3.2.** Statistical Analysis

A repeated measures GLIMMIX was used to determine the effects of crop residue treatment, cycle, incubation period, and their interactions on NO<sub>3</sub>-N mineralization. As the measurements of NO<sub>3</sub>-N mineralization collected from same experimental tube unit are correlated over time, the model was correlated by imposing certain covariance structure on the error term of the model. Akaike's Information Criteria (AIC) was used to determine the appropriate covariance structure and the smaller AIC value the better. Throughout this paper, AR(1) covariance structure was used due to it always producing the smallest AIC value. The least square mean (LS-mean) of each level of the freeze and thaw cycles was estimated and the significance of the difference between all possible pairs of these LS-means was identified with Tukey's Honest Significant Difference (HSD) at a significance level of 0.05. In addition, LS-means of each individual crop residue treatment within each freeze and thaw cycle was estimated

and HSD test with a significance level of 0.05 was performed to test the significant difference among all possible pairs of the LS-means. Moreover, LS-means of each individual crop residue treatment for each incubation period within each freeze and thaw cycle was estimated and HSD test with a significance level of 0.05 was used to find the LS-means that are significantly different from each other.

In order to detect the change of NO<sub>3</sub>-N mineralization for the bare, unamended soil over incubation periods for each freeze and thaw cycle, a simple one-way ANOVA with repeated measurements model was fitted. LS-means of each incubation period within each freeze and thaw cycle was estimated and HSD test was used to find the LS-means that are significantly different from each other. All analyses were conducted by SAS version 9.4 (SAS Institute, 2013).

### 4.4. Results and Discussion

Mean soil NO<sub>3</sub>-N mineralization capacity for individual crop residue treatments varies among freeze and thaw cycles from 1.88 mg NO<sub>3</sub>-N kg<sup>-1</sup> to 58.97 mg NO<sub>3</sub>-N kg<sup>-1</sup> (Table 4). The mean soil NO<sub>3</sub>-N mineralization capacity (range in means) peaks during cycle 3, while displaying the narrowest range in mean soil NO<sub>3</sub>-N mineralization capacity in cycle 5. Freeze and thaw cycle means varied from 4.95 mg NO<sub>3</sub>-N kg<sup>-1</sup> to 17.84 mg NO<sub>3</sub>-N kg<sup>-1</sup> with cycle 4 and 5 significantly higher than cycles 1, 2, and 3. For all freeze and thaw cycles, the control (bare, unamended soil) means shows net N mineralization varying from 1.74 mg NO<sub>3</sub>-N kg<sup>-1</sup> to 22.72 mg NO<sub>3</sub>-N kg<sup>-1</sup>. Both cycle 4 and cycle 5 display higher mean soil NO<sub>3</sub>-N mineralization values for the bare, unamended soil (22.72 mg NO<sub>3</sub>-N kg<sup>-1</sup> and 18.45 mg NO<sub>3</sub>-N kg<sup>-1</sup>, respectively) and it is important to note that the higher control values contribute to the narrowing of the range mineralization capacity in the later freeze and thaw cycles. This increase observed in the bare,

unamended soil may be due to a natural microbial shift as an adaptation to the fact that no carbon source was added to the system in the controls. In other words, microbes in the bare, unamended soil recognize no carbon source addition and start to consume SOM in those controls as an energy source whereby NO<sub>3</sub>-N is being released.

When examining the five incubation cycles, the forage radish and pea are the only crop residue treatments that show a significant increase in the soil NO<sub>3</sub>-N mean from the control (Figure 9).

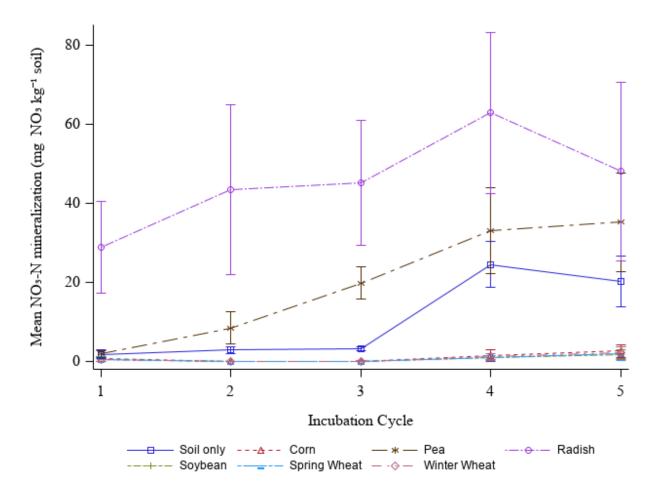


Figure 9. NO<sub>3</sub>-N mineralization means and range in value for soil control and corn, pea, radish, soybean, spring wheat, and winter wheat crop residue treatment over five incubation cycles.

Table 4. Mean and cumulative soil NO<sub>3</sub>-N mineralization over six incubation periods and five free-thaw cycles with overall mean for corn, flax, pea forage radish, soybean, spring wheat, and winter wheat crop residues and cycle means showing significant differences for the Foreman soil series in North Dakota.

			Nitrogen mineralization, mg NO <sub>3</sub> kg <sup>-1</sup> soil									
Cycle	Crop Residue	1 <sup>st</sup>	$2^{\text{nd}}$	$3^{\rm rd}$	4 <sup>th</sup>	5 <sup>th</sup>	6 <sup>th</sup>	Cumulative	Overall Mean <sup>±</sup>	Cycle Mean <sup>‡</sup>		
·	Treatment	(14 d.)	(28 d.)	(42 d.)	(56 d.)	(70 d.)	(84 d.)			•		
1 <sup>st</sup>	Soil only	1.990b <sup>†</sup>	0.080a	0.970ab	2.923b	2.293b	2.387b	10.64b	$1.741b \pm 2.21$	4.95b		
	Corn	3.667b	0.017a	0.001b	0.073b	0.000b	0.017b	3.773b	$0.534b \pm 1.40$			
	Pea	2.290b	0.097a	1.513ab	2.843b	2.250b	2.547b	11.54b	$1.884b \pm 1.67$			
	Radish	55.147a	1.533a	26.053a	37.660a	37.680a	14.927a	173.0a	$28.34a \pm 23.3$			
	Soybean	2.300b	0.063a	0.001b	0.223b	0.223b	0.150b	2.960b	$0.436b \pm 0.85$			
	Spring Wheat	3.200b	0.017a	0.001b	0.100b	0.103b	0.080b	3.500b	$0.500b \pm 1.21$			
	Winter Wheat	2.283b	0.001a	0.001b	0.090b	0.001b	0.057b	2.430b	$0.345b \pm 0.87$			
$2^{\text{nd}}$	Soil only	0.953ab	4.227bc	3.607b	1.813b	4.053b	4.657bc	19.31b	$3.214b \pm 1.78$	9.03b		
	Corn	0.000b	0.190c	0.002b	0.006b	0.000b	0.003c	0.193b	$0.032b \pm 0.09$			
	Pea	0.363b	11.433b	9.647b	7.770ab	15.987ab	13.693ab	58.89b	$9.789b \pm 8.99$			
	Radish	14.090a	143.87a	68.55a	26.76a	25.820a	21.353a	300.4a	$49.77a \pm 47.9$			
	Soybean	0.000b	0.000c	0.093b	0.000b	0.103b	0.153c	0.350b	$0.058b \pm 0.13$			
	Spring Wheat	0.000b	0.000c	0.013b	0.001b	0.000b	0.050c	0.063b	$0.011b \pm 0.04$			
	Winter Wheat	0.000b	0.037c	0.001b	0.001a	0.000b	0.017c	0.053b	$0.009b \pm 0.03$			
3 <sup>rd</sup>	Soil only	2.583b	3.130b	3.130b	3.257b	3.437b	3.193b	18.73b	$2.989b \pm 0.89$	10.22b		
	Corn	0.000b	0.000b	0.000b	0.000b	0.001b	0.013b	0.013b	$0.005b \pm 0.01$			
	Pea	21.730b	18.947b	18.947b	14.570b	19.21a	21.967a	115.4ab	$20.7ab \pm 8.70$			
	Radish	110.95a	52.540a	52.540a	33.680a	23.27a	21.90a	294.9a	$58.97a \pm 36.1$			
	Soybean	0.000b	0.000b	0.000b	0.030b	0.000b	0.013b	0.043b	$0.007b \pm 0.02$			
	Spring Wheat	0.067b	0.000b	0.000b	0.003b	0.001b	0.020b	0.090b	$0.031b \pm 0.04$			
	Winter Wheat	0.000b	0.000b	0.000b	0.003b	0.000b	0.113b	0.117b	$0.041b \pm 0.05$			
4 <sup>th</sup>	Soil only	6.550a	17.53ab	33.31ab	24.12b	32.57b	32.84ab	147.0ab	$22.7ab \pm 11.8$	17.84a		
•	Corn	0.187b	0.350b	5.320b	1.833b	0.480c	0.490b	8.660b	$1.033b \pm 2.87$	17.0.14		
	Pea	4.190ab	19.80ab	28.30ab	46.06ab	54.68ab	45.59a	198.6ab	$30.1ab \pm 21.7$			
	Radish	8.420a	60.42a	78.41a	88.58a	76.29a	65.15a	377.3a	$53.23a \pm 40.9$			
	Soybean	0.000b	0.930b	2.123b	1.190b	0.867c	0.687b	5.797b	$0.735b \pm 1.05$			
	Spring Wheat	0.427b	0.573b	0.830b	2.393b	0.593c	0.333b	5.150b	$0.681b \pm 1.39$			
	Winter Wheat	0.000b	0.723b	1.493b	3.060b	0.617c	1.000b	6.893b	$0.908b \pm 1.46$			
5 <sup>th</sup>	Soil only	26.46a	30.97a	28.50b	27.52bc	8.187bc	0.000b	121.6ab	$18.4ab \pm 12.9$	16.03a		
	Corn	0.793b	0.870a	7.513b	5.313c	1.037cd	0.000b	15.53b	$2.019b \pm 3.32$			
	Pea	40.74a	56.54a	51.11ab	53.27ab	9.687b	0.000b	211.3ab	$31.4ab \pm 25.1$			
	Radish	26.21a	44.77a	97.96a	86.76a	25.44a	7.307a	288.4a	$39.95a \pm 45.5$			
	Soybean	0.000b	1.530a	6.137b	2.840c	0.063d	0.000b	10.57b	$1.304b \pm 2.38$			
	Spring Wheat	0.777b	0.810a	4.593b	5.537c	0.470cd	0.000b	12.19b	$1.605b \pm 3.52$			
	Winter Wheat	0.001a	0.997a	6.297b	5.427c	0.727cd	0.000b	13.45b	$1.659b \pm 3.07$			

<sup>†</sup>Different letters within a column for each incubation cycle are significantly different at the 0.05 level using Tukey's HSD test.

<sup>&</sup>lt;sup>±</sup> Nitrogen mineralization mean over all incubation periods for each crop residue treatment.

<sup>\*</sup>Nitrogen mineralization mean over all incubation periods including all crop residue treatments.

During cycle 1, the forage radish is the only crop residue treatment significantly different from the other crop residues treatment (Figure 10). At cycle 2, the soil NO<sub>3</sub>-N mean increases in both the bare, unamended soil (control) and the pea crop residue treatment, although are still significantly different from the forage radish crop residue treatment (Figure 11).

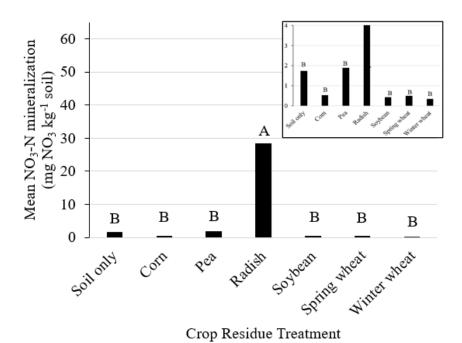


Figure 10. Mean soil NO<sub>3</sub>-N mineralization patterns for control, corn, pea, radish, soybean, spring wheat, and winter wheat crop residue treatments for the first incubation cycle. Inset shows mean NO<sub>3</sub>-N immobilization for corn, soybean, spring wheat and winter wheat and mean NO<sub>3</sub>-N mineralization for pea, though not significantly different from the soil only.

During cycle 3, the forage radish crop residue treatment still remains significantly different from the control; although both are similar to soil NO<sub>3</sub>-N mean for the pea crop residue treatment (Figure 12). In cycle 4 and cycle 5, the bare, unamended soil (control) and the pea crop residue treatment are not significantly different from the forage radish nor were they significantly different from the corn, soybean, spring wheat and winter wheat crop residue treatments (Figure 13 and 14). By cycle 5, it is evident that the corn, soybean, spring wheat and winter wheat crop residue treatments were not mineralizing soil NO<sub>3</sub>-N and were always

significantly different from the forage radish crop residue treatment. A reason for the observations in these mineralization patterns is the C:N ratio for each crop residue treatment influences the N mineralization characteristic of the residue (Aher et al., 2016).

For example, the forage radish (C:N=8) NO<sub>3</sub>-N mineralization mean is significantly higher when compared to each crop residue treatment and the bare, unamended soil during all five freeze and thaw cycles. Pea (C:N=18) shows increased N mineralization over the bare, unamended soil in all five freeze and thaw cycles, with a steady increase in mineralization beginning in cycle 3 and beyond. All other crop residue treatments with higher C:N ratios (corn (C:N=73), soybean (C:N=53), spring wheat (C:N=76), and winter wheat (C:N=101)) exhibit patterns of soil NO<sub>3</sub>-N immobilization.

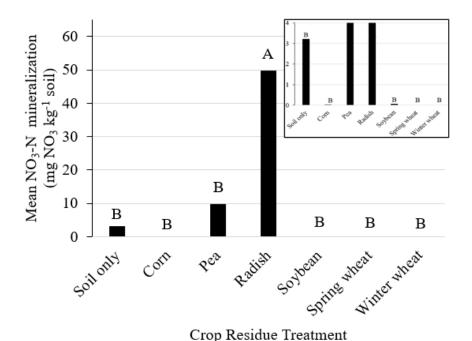
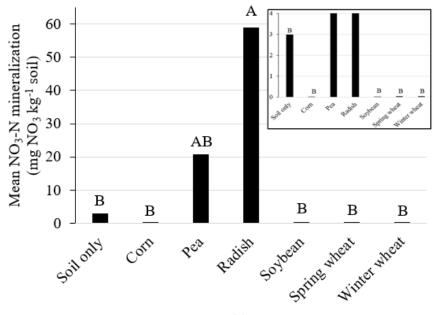
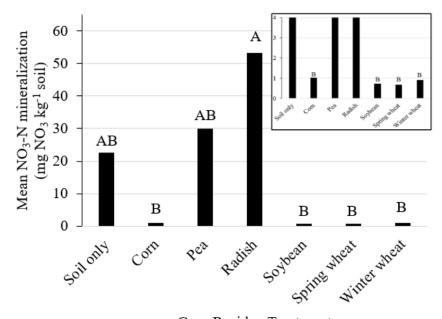


Figure 11. Soil NO<sub>3</sub>-N mineralization mean patterns for control, corn, pea, radish, soybean, spring wheat, and winter wheat crop residue treatments for the second incubation cycle. Inset shows mean NO<sub>3</sub>-N immobilization for corn, soybean, spring wheat and winter wheat not significantly different from the soil only.



Crop Residue Treatment

Figure 12. Soil NO<sub>3</sub>-N mineralization mean patterns for control, corn, pea, radish, soybean, spring wheat, and winter wheat crop residue treatments for the third incubation cycle. Inset shows mean NO<sub>3</sub>-N immobilization for corn, soybean, spring wheat and winter wheat not significantly different from the soil only.



Crop Residue Treatment

Figure 13. Soil NO<sub>3</sub>-N mineralization mean patterns for control, corn, pea, radish, soybean, spring wheat, and winter wheat crop residue treatments for the fourth incubation cycle. Inset shows mean NO<sub>3</sub>-N immobilization for corn, soybean, spring wheat and winter wheat similar to the soil only.

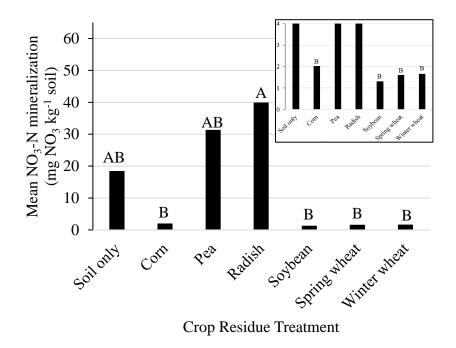


Figure 14. Soil NO<sub>3</sub>-N mineralization mean patterns for control, corn, pea, radish, soybean, spring wheat, and winter wheat crop residue treatments for the fifth incubation cycle. Inset shows mean NO<sub>3</sub>-N immobilization for corn, soybean, spring wheat and winter wheat similar to the soil only.

Closer examination of the mean soil NO<sub>3</sub>-N mineralization patterns over freeze and thaw cycles (Figure 9) indicates a wide range in soil NO<sub>3</sub>-N variation from the mean that is consistent for the forage radish crop residue treatment. This is because the forage radish crop residue possesses available N and other nutrients required by microorganisms, in addition to what the soil harbors itself; therefore, the microbes have plentiful food options based upon their wants and needs and N contained in the plant material (Roesler, 2016). Conversely, the wider C:N ratio crops (corn, soybean, spring wheat, and winter wheat) exhibit narrower soil NO<sub>3</sub>-N variation from the mean N mineralization from the soil and possess limited nutrient availability to the soil, creating an environment much harder for microbes to extract nitrogen, illustrating the inverse relationship with the C:N ratio (i.e. as the C:N ratio decreases, range increases). With this information alone, it appears that freeze and thaw effects on mean soil NO<sub>3</sub>-N mineralization appears to vary based on crop residue treatment and the C:N ratio of the material.

The bare, unamended soil, absent of any crop residue treatment, shows a cumulative soil NO<sub>3</sub>-N mineralization pattern that increases with freeze and thaw cycles. Cumulative values of soil NO<sub>3</sub>-N mineralization of the five cycles are 11, 19, 19, 147, and 122 mg NO<sub>3</sub>-N kg<sup>-1</sup>, respectively (Table 1). From this, it is evident that soil NO<sub>3</sub>-N mineralization in the control itself is increasing, in the absence of any crop residue on the soil surface. This cumulative build up may be evidence of the microbial shift mentioned previously that is preferentially attacking the native SOM. Because there is no carbon source added to the soil, microbes compete for a relatively stable (C:N=10-12) nutrient source, whereby nitrogen is then released from stable SOM.

When examining soil NO<sub>3</sub>-N mineralization further and over the incubation periods for each crop residue treatment, mineralization shifts from periods representing the early in growing season towards the mid-growing season periods with increased freeze and thaw cycles. For example, during the first freeze and thaw cycle, day 14 soil NO<sub>3</sub>-N mineralization values are significantly higher than the other incubation periods (days) for each crop residue treatment (Figure 15). During the second freeze and thaw cycle, day 28 soil NO<sub>3</sub>-N mineralization is significantly higher for all crop residue treatments and day 14 show the lowest soil NO<sub>3</sub>-N mineralization values overall (Figure 16). In cycle 3, no significant differences occur among incubation periods for all crop residue treatments (Figure 17). The shift becomes evident in the fourth freeze and thaw cycle where soil NO<sub>3</sub>-N mineralization is significantly different on day 42, 56, and 70 from the other incubation periods (Figure 18). In the fifth freeze and thaw cycle, soil NO<sub>3</sub>-N mineralization is significantly higher in the mid-growing season (day 42) from all other incubation periods, while day 84 indicates significantly lower soil NO<sub>3</sub>-N mineralization values (Figure 19). This pattern of NO<sub>3</sub>-N mineralization release with the increasing number of

freeze and thaw cycles is of importance to pinpoint when nutrients might be available to plants. From this analysis, increased freeze and thaw cycles can contribute to nutrient availability in the mid-growing season period, when plants often need it the most.

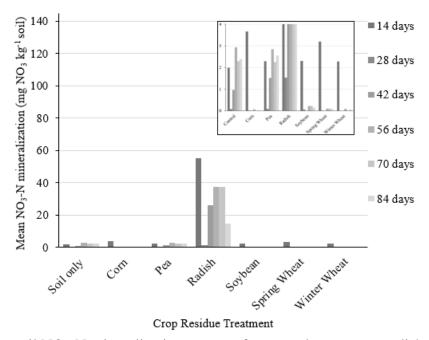


Figure 15. Mean soil NO<sub>3</sub>-N mineralization patterns for control, corn, pea, radish, soybean, spring wheat, and winter wheat crop residue treatments by incubation period for the first incubation cycle. Inset shows the peak in mean NO<sub>3</sub>-N mineralization for corn, soybean, spring wheat and winter wheat early in the growing season during the first incubation cycle.

When more narrowly considering the individual crop residue treatments and their contributions to soil NO<sub>3</sub>-N mineralization averaged over all incubation cycles these can be ranked as forage radish > pea > bare, unamended soil  $\geq$  corn = winter wheat = spring wheat = soybean (47.80 > 19.86 > 10.57 > 0.94 = 0.76 = 0.70 = 0.66 mg NO<sub>3</sub>-N kg<sup>-1</sup>, respectively). Forage radish is significantly different from all crop residues treatments and the bare, unamended soil. The pea crop residue treatment is significantly different from the bare, unamended soil. The corn, soybean, spring wheat and winter wheat crop residue treatments are always less than mg NO<sub>3</sub>-N kg<sup>-1</sup>, are similar, and significantly different from the forage radish, pea, and unamended, soil control.

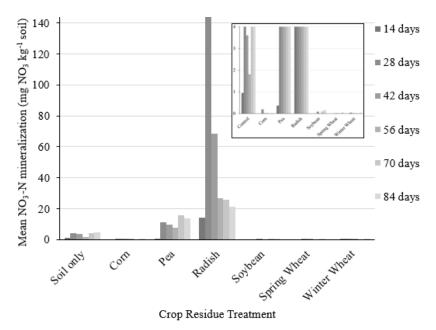


Figure 16. Mean soil NO<sub>3</sub>-N mineralization patterns for control, corn, pea, radish, soybean, spring wheat, and winter wheat crop residue treatments by incubation period for the second incubation cycle. Inset shows net soil NO<sub>3</sub>-N immobilization for corn, soybean, spring wheat and winter wheat during the second incubation cycle.

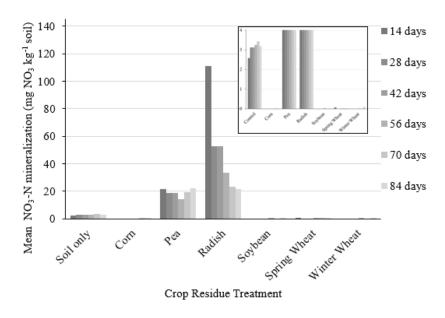


Figure 17. Mean soil NO<sub>3</sub>-N mineralization patterns for control, corn, pea, radish, soybean, spring wheat, and winter wheat crop residue treatments by incubation period for the third incubation cycle. Inset shows net soil NO<sub>3</sub>-N immobilization for corn, soybean, spring wheat and winter wheat during the third incubation cycle.

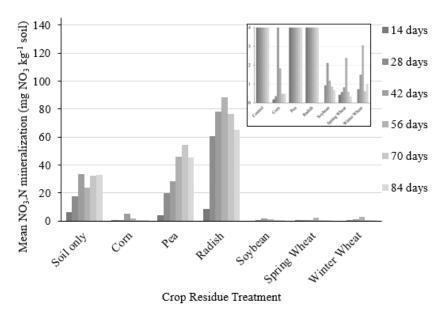


Figure 18. Mean soil NO<sub>3</sub>-N mineralization patterns for control, corn, pea, radish, soybean, spring wheat, and winter wheat crop residue treatments by incubation period for the fourth freeze incubation cycle. Inset shows net soil NO<sub>3</sub>-N immobilization for corn, soybean, spring wheat and winter wheat during the second incubation cycle with peak NO<sub>3</sub>-N fluxes occurring during the early to mid-growing season.

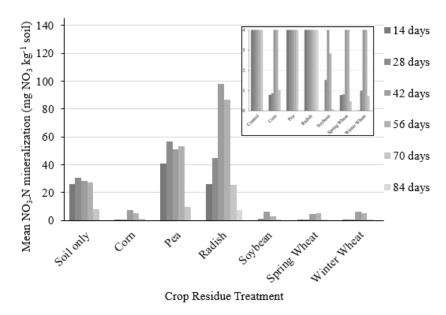


Figure 19. Mean soil NO<sub>3</sub>-N mineralization patterns for control, corn, pea, radish, soybean, spring wheat, and winter wheat crop residue treatments by incubation period for the fifth incubation cycle. Inset shows net soil NO<sub>3</sub>-N immobilization for corn, soybean, spring wheat and winter wheat during the second incubation cycle with peak NO<sub>3</sub>-N fluxes occurring during the mid to late growing season.

Figures 20, 21, 22, 23 and 24 show the average daily trends of soil NO<sub>3</sub>-N mineralization and immobilization from the crop residue treatments during each incubation cycle (n=5) to determine whether NO<sub>3</sub>-N in the crop residue contributes to N availability in the soil. The bare, unamended soil is represented by the zero line. Above the zero line indicates N mineralization, while below the zero line suggests N immobilization. Mineralization/immobilization quantities differ based on the number of incubation cycles. Daily mineralization and immobilization NO<sub>3</sub>-N values ranged from -0.20 to 2.53 mg NO<sub>3</sub>-N kg<sup>-1</sup> for the first cycle, from -0.34 to 18.61 mg NO<sub>3</sub>-N kg<sup>-1</sup> for the second cycle, from -0.30 to 7.74 mg NO<sub>3</sub>-N kg<sup>-1</sup> for the third cycle, from -2.32 to 4.60 mg NO<sub>3</sub>-N kg<sup>-1</sup> for the fourth cycle, and from -2.15 to 4.96 mg NO<sub>3</sub>-N kg<sup>-1</sup>. From these figures it is evident that forage radish and pea are the only crops mineralizing at or above the bare, unamended soil control levels. All other crops (corn, soybean, winter wheat, and spring wheat) show N immobilization for each leaching of every incubation cycle. These N mineralization/immobilization trends are consistent with the results provided earlier from crops with a narrower C:N ratio being the only ones to show mineralization above the bare, unamended soil. Patterns of the average daily NO<sub>3</sub>-N mineralization/immobilization trends are also similar to the trends observed when examining the overall mean for each freeze and the cycle where increases are observed in the earlier growing season for the cycles 1 and 2 and where increased are observed in the mid to late growing season in cycle 4 and 5. These patterns are also generally consistent regardless if above or below the control, although are heavily influenced by the forage radish results.

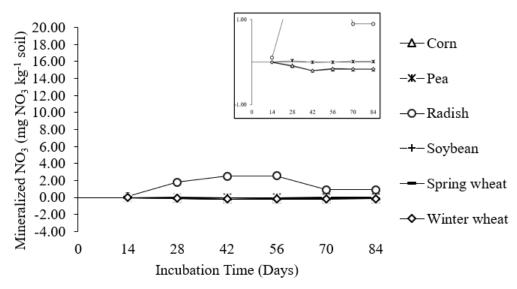


Figure 20. Daily mean mineralization/immobilization of soil NO<sub>3</sub>-N for the Forman soil series during the first incubation cycle. Inset shows slight mineralization of pea early in the growing season then parallel with the soil itself, while corn, soybean, spring wheat and winter wheat are immobilizing.

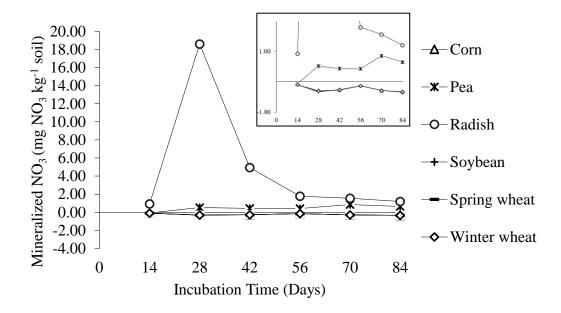


Figure 21. Daily mean mineralization/immobilization of soil NO<sub>3</sub>-N for the Forman soil series during the second incubation cycle. Inset shows mineralization of pea for the duration of the growing season and immobilization of corn, soybean, spring wheat and winter wheat.

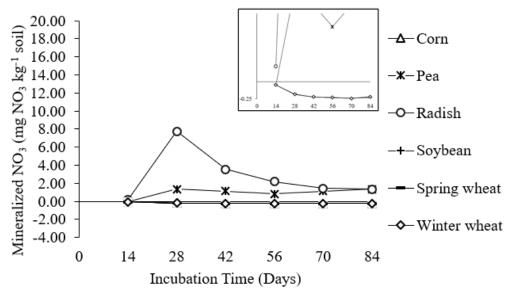


Figure 22. Daily mean mineralization/immobilization of soil NO<sub>3</sub>-N for the Forman soil series during the third incubation cycle. Inset shows immobilization of corn, soybean, spring wheat, and winter wheat.

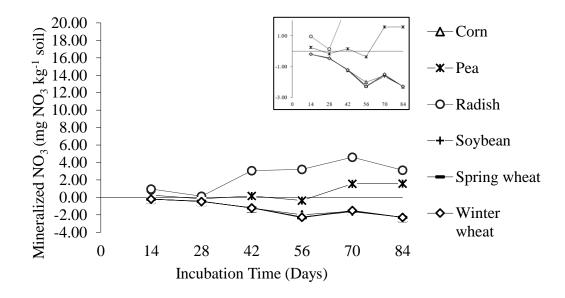


Figure 23. Daily mean mineralization/immobilization of soil NO<sub>3</sub>-N for the Forman soil series during the fourth incubation cycle. Inset shows variation of mineralization and immobilization of pea during most of the growing season and immobilization of corn, soybean, spring wheat, and winter wheat.

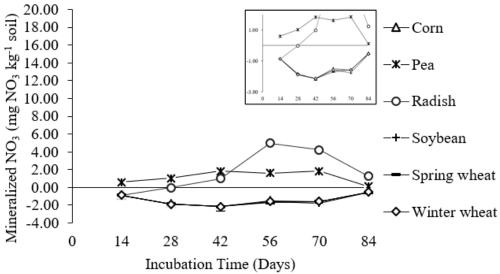


Figure 24. Daily mean mineralization/immobilization of soil NO<sub>3</sub>-N for the Forman soil series during the fifth incubation cycle. Inset shows radish mineralizing in the mid-growing season and immobilization with corn, soybean, spring wheat and winter wheat.

# 4.5. Conclusion

Accumulation of crop residue on top of soil surface did not increase soil NO<sub>3</sub>-N mineralization. Narrow C:N ratio crop residue treatments influenced the rate of soil NO<sub>3</sub>-N mineralization as was evident with the forage radish and pea crop residue treatments being the only ones to mineralize. This can help to inform freeze and thaw effects on NO<sub>3</sub>-N mineralization in a fridge environment such as the Northern Great Plains where producers are limited to short growing season. The number of incubation cycles may have had a direct effect on the mineralization process for all the crop residue treatments where cycle 4 and cycle 5 were noted to release the most NO<sub>3</sub>-N, particularly in the mid to late growing season as cycles increase. Wide C:N ratio crop residue such as corn, soybean, spring wheat, and winter wheat showed a net immobilization effect for every incubation cycle. The bare, unamended soil showed a cumulative increase in NO<sub>3</sub>-N mineralization cycle-over-cycle. It would have been expected that addition of a carbon source to the soil surface, in the form of crop residue, would have been at or above the rate of the control. This was not found to be true and indicates a state where

degradation of the native SOM occurs which may eventually contribute to soil degradation. In other words, the absence of a carbon source addition may lead microorganisms to seek a carbon source from the soil itself. When this occurs, it is due to the lack of nutrient substrate from organic matter. Thus, the microorganisms themselves release nutrients including nitrogen from the organic matter in the bare, unamended soil. The addition of nitrogen fertilizer may aid to facilitate soil NO<sub>3</sub>-N mineralization in fields under a long-term no till system with wide C:N ratio crop residues to offset the mineralization of N by decomposing residues.

There are several directions in future research that can be informed by our results. Further studies should examine the effect of freeze and thaw cycle as well as the microbial count and community to better understand soil NO<sub>3</sub>-N mineralization source and sink. Microbes require nitrogen as a nutrient source, thus limited nutrients in a cropping system may be observed where volume of crop residue and the recommended fertilizer additions or credits are not equitable. In addition, further studies incorporating increased fertilizer may provide insights on impacts to wide C:N ratio crop residues on NO<sub>3</sub>-N mineralization source and sink. One limitation of this study was the homogenous crop residue on the soil surface; whereas in a field setting, a mixed residue application (i.e. non-leguminous mixed with cover crop) would more closely align with field conditions in a production environment.

# 4.6. References

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# 5. INTERACTION EFFECTS OF MIXED CROP RESIDUE AND SOIL FREEZE-THAW ON PLANT AVAILABLE NITROGEN

### 5.1. Abstract

Cover crops are known to improve soil health, conserve soil moisture, increase soil organic matter (SOM), reduce soil erosion and compaction, and improve the soil microbial community, while also reducing N lost by leaching and runoff. In North Dakota, a climate having cool temperatures ( $\sim 5^{\circ}$ C), a short growing season (100-135 frost free days), and commonly grown crops with wide C:N ratios, a heavy accumulation of residue (8 to 10 Mg ha<sup>-1</sup>) have been observed in long-term no-till cropping systems. Although cover crops are being promoted to scavenge and capture residual nitrogen in the soil for the following growing season, little is still known about their impacts in wide C:N crop residue interaction with narrow C:N ratio crop residue especially when heavy crop residue accumulations occurs in long term no-till systems. A long-term lab incubation study was conducted to measure mineralizable NO<sub>3</sub>-N in simulated 2-year and 3-year crop rotations similar to those found in the northern Great Plains utilizing a Forman clay loam soil (fine-loamy, mixed, superactive, frigid Calcic Argiudolls), plus 3-year with cover crop at 15% incorporation. The combination of crops included corn (Zea mays L.), soybean (Glycene max L.), and spring wheat (Triticum aestivum L.). All combinations of crops were subject to three freeze-thaw cycles with addition of residues of a successive crop after each thaw in the cycle. Treatments with 15% forage radish (Raphnus sativis L.) were mixed with either spring wheat or soybean residue to evaluate effects in offsetting N immobilization by high C:N crop residues. Results of this study show that incorporating narrow C:N ratio cover crops residues such as radish with other wider C:N ratio crops such as corn, soybean and winter wheat

in a rotation component of the cropping system did not offset N immobilization by wide C:N ratio crops.

### 5.2. Introduction

Often high levels of crop residue remain on the soil surface in North Dakota, specifically where corn (*Zea mays* L.) or wheat (*Triticum aestivum* L.) are the primary crops in a rotation and are grown under conservation tillage conditions (Aher et al, 2016; Chatterjee et al., 2016). The accumulation of residue on the soil surface is partly due to field management practices (eg. reduced tillage, no-till), but also a result of the climatic conditions of the region. The relatively cool climate in the northern Great Plains of the U.S., residue decomposition and nutrient mineralization from these residues can be limited by a short frost-free period of 100-135 days (NOAA, 2020). The interaction between the residue of a low C:N ratio crop mixed with corn or wheat residue is unknown especially when making fertilizer recommendations for a high N requirement crops, like corn. There is scant information from the literature into crop N requirements in conservation or no-till systems with high residue accumulation especially in cool climate environments.

Including a low C:N ratio cover crop in a crop rotation where high C:N ratio crop residue exists may alter the soil NO<sub>3</sub>-N immobilization of decomposing non-leguminous crops to improve soil NO<sub>3</sub>-N mineralization and availability. Rutan and Stienke (2019) while evaluating daikon radish (*Raphanus sativus* L.) and forage oat (*Avena sativa* L.) cover crops following winter wheat proceeding corn, concluded that although cover crop increased sequestration of NO<sub>3</sub>-N in the fall, it did not translate to providing available NO<sub>3</sub>-N in the soil to support needs of the corn crop during the following growing season. Nevins et al. (2020) examined C and N release from cereal rye (*Secale cereale* L.) and hairy vetch (*Vicia villosa* L.) cover crop residues

and concluded that including them into a crop rotation with corn and/or soybean did not affect C or N release in the soil. A study by Vigil et al. (2002) found that winter wheat/corn/summer fallow rotation harbored greater N immobilization and decreased N mineralization as a result of the increased quantity of crop residue as compared to the winter wheat/summer fallow rotation. Others have concluded that more intensive cropping systems increase soil organic matter (SOM) thus increasing N mineralization under conservation tillage practices (Ortega et al., 2002; Wienhold and Halvorson, 1999). However, additional studies concluded that there are no differences in N mineralization between less or more intensive cropping systems (Ortega et al., 2005).

In nature, the C:N ratios of crop residue are different and unique on their own. Generally, crops with a high C:N ratio (corn (*Zea mays* L.), wheat (*Triticum* L.) have a lower N mineralization rate than crops with lower C:N ratios [i.e. soybean (*Glycine max* L.), alfalfa (*Medicago sativa* L.)]. When crops are rotated in a field, the C:N ratios of the system may be altered resulting in soil N mineralization or immobilization values which vary from those observed by each crop on its own (Chatterjee et al., 2016). Despite crop residue containing potential pools of nitrogen, this does not always translate into mineralizable nitrogen and plant available nitrogen in the soil. Vanotti and Bundy (1995) studied the incorporation of soybean into cropping systems over fifteen years on soil nitrogen availability and found that crop yields immediately following incorporation of soybean were greatest in comparison to rotations that did not incorporate soybean. This increase in yield was attributed to greater available soil N as a result of increase SOM, though these benefits did not translate to the second year following soybean incorporation. Hapka et al. (2000) examined the time and release of nitrogen from various crop residues (canola (*Brassica napus* L.), corn (*Zea mays* L.), potato (*Solanum* 

tuberosum L.), sugarbeet (*Beta vulgaris* L.), sunflower (*Helianthus* L.), and wheat (*Triticum* L.)) and their decomposition to subsequent crops finding that the sugarbeet and potato (low C:N ratios) had a higher N mineralization rate earlier in the growing season as compared to the other crops (high C:N ratios). This finding was significant as sugarbeet and potato contribution N to the soil when plants need it most. In their study, the sugarbeet and potato crops justified an N fertilizer credit of between 56 and 112 kg N ha<sup>-1</sup>. Corn and wheat decomposed at a similar rate to each other, mineralized significantly less N, and did not justify a N fertilizer credit. However, this study measured residue mass disappearance N loss from the decomposing material but did not determine the amount released to the soil.

Current recommendations in the state of North Dakota are to provide a 22 kg N ha<sup>-1</sup> credit for no-till systems of 5 years or less and a 34 kg N ha<sup>-1</sup> credit for N-till systems of 6 years or greater (Franzen et al., 2018). However, the interaction between the residue of a legume or cover crop mixed with corn or wheat residue is unknown especially when making recommendations for a high N requirement crop like corn. Numerous states in the northern U.S. have recommended that long-term no-till systems require a greater N fertilizer inputs to achieve maximum yield potential when heavy crop residue is present (Stecker et al., 1995; Bundy, 1998; Ketterings et al., 2003; Jokela et al., 2004; Halvorson et al., 2006; Liu and Wiatrak, 2012; Dinkins and Jones, 2019). Aher et al. (2016) examined the C:N ratios and mass of crop residue remaining on the soil surface near Forman, ND. They concluded the possibility of an N deficit of between 56-108 kg N ha<sup>-1</sup> for succeeding crops seeded in long-term no-till. Chatterjee et al. (2016) stated that lengthy and diversified cropping systems might be helpful in increasing nutrient availability in the inorganic forms by reducing the decomposition of the crop residue (i.e. if microbes have nutrients available in the soil in the form preferred). This research and its

findings should help farmers gain more clarity on crop N needs in long-term no-till fields. Also, this research should provide insights to NDSU and encourage revisiting crop N recommendations. Gaining a better understanding of residue decomposition with more intensive cropping rotations and resulting mineralization or immobilization of NO<sub>3</sub>-N in the northern Great Plains will help to better inform producers on residue management approaches and practices with fertilizer application.

The objectives of this study are to 1.) determine the soil N mineralization and immobilization in a sequence of crops in typical North Dakota rotations in a long-term no-till system, 2.) determine soil N mineralization or immobilization when incorporating high C:N crop residue into low C:N cover crop residue, and 3.) evaluate the impact of freeze and thaw cycles on the NO<sub>3</sub>-N mineralization.

### **5.3.** Materials and Methods

# **5.3.1.** Experimental Design

A laboratory study using a randomized complete block design with three replicates was set up using one soil series with four crop residue and eleven residue combinations, plus one bare, unamended soil control. The soil was from a bulk sample of the Forman (Fine-loamy, mixed, superactive, frigid Calcic Argiudolls) soil series (Soil Survey Staff, 1998). This soil was selected as it is similar to many of the most common soil series in the region. Soil was collected from the Conservation Cropping System Project (CCSP) site (Aher, et al., 2016) near Forman, North Dakota. The study contained three replicates of eleven residue treatments, plus a bare, soil control and radish alone control (n=39). The four residue treatments were: corn (*Zea mays* L.) (C) (C:N = 57), soybean (*Glycine max* L.) (S) (C:N = 70), spring wheat (*Triticum aestivum* L.) (SW) (C:N = 43), and forage radish (*Raphanus sativus* L.) (R)(C:N = 11.8) (Table 5).

The fresh residue was collected immediately after the fall harvest in the vicinity of Fargo, North Dakota. Upon collection, residue was oven dried at  $60^{\circ}$ C and ground in a Wiley mill to pass a < 2 mm screen and analyzed for its chemical composition using an Elementar Vario Max® CN analyzer. The bulk soil samples were air dried, crushed, and sieved through a 2 mm screen.

Table 5. Crop residues, scientific names and carbon:nitrogen (C:N) ratios used in this study.

Crop Residue Treatment	Scientific Name	C:N Ratio
Corn	Zea mays L.	57
Forage Radish	Raphanus sativus L.	11.8
Soybean	Glycine max L.	70
Spring Wheat	Triticum aestivum L.	43

A variation of the long-term incubation and leaching techniques of Sanford and Smith (1972) was utilized where crop residues (n=39) were prepared containing 15 g of soil mixed with 15 g of quartz sand (20 mesh) to facilitate leaching with 0.50 g of residue applied to the soil surface according to the treatment schedule in Table 6 for the two-year rotations (n=5), threeyear rotations (n=3), and three-year rotations with cover crops (n=3). For the three-year rotation with cover crop, radish was incorporated with spring wheat and soybean residue at fifteen percent of the 0.50 g of total residue. The forage radish cover crop was combined with only soybean and spring wheat because of the ability of farmers to more easily incorporate cover crops with early harvested crops. The untreated, bare soil controls (n=3) contained 15 g of soil mixed with 15 g of sand only. Samples were then transferred to labeled glass leaching tubes where soil mixture was placed into the tube and crop residue was then placed on top of the soil surface to simulate no-till residue accumulation. Leaching tubes were kept in a constant temperature room at 22°C and were incubated as described by Stanford and Smith (1972). Before the soil samples were transferred to the leaching tubes, a small amount of glass wool was placed in the bottom of the leaching tubes to prevent soil sediment loss during leaching and at the top to prevent soil and residue disturbance during application of the leaching solution.

Table 6. Crop residue treatment and rotations for corn (C), soybean (S), forage radish (R), spring wheat (SW), and the bare, unamended soil and radish only controls.

Type of Rotation	Crop Rotation Treatments				
	0.50 g/individual crop residue				
Control	Soil only				
	Radish only				
2-Year	C-C-C				
	C-S-C				
	S-C-S				
	SW-S-SW				
	S-SW-S				
3-Year	SW-S-C				
	S-C-SW				
	C-SW-S				
3-Year with Cover Crops <sup>†</sup>	SW/R-S/R-C				
•	S/R-C-SW/R				
	C-SW/R-S/R				

<sup>&</sup>lt;sup>†</sup>Forage radish was incorporated at fifteen percent of the 0.50g for each individual crop residue

Each incubation series represented an annual growing season and a three-week freeze period (-5°C) was imposed between the first and second, and again between the second and third incubation period to represent an annual freeze/thaw cycle (winter season). Following each freeze and thaw cycle (n=3), 0.5 g of fresh crop residue was placed on the soil surface (total of 1.5 g per leaching tube over the period of the study) based on the crop schedule in Table 2. Biweekly leaching of the incubations were then conducted at 2, 4, 6, 8, 10, and 12 weeks covering the average duration of a North Dakota growing season. Prior to these leachings, an initial 50 mL of 0.01M CaCl<sub>2</sub> was added to the glass tubes in 10 mL increments followed by 10 mL of nutrient solution as described by Stanford and Smith (1972) to remove ambient levels of NH<sub>4</sub>+ and NO<sub>3</sub>-N. For each leaching of the samples, 30 mL of 0.01M CaCl<sub>2</sub> was added to the glass tubes in 10 mL increments followed by 10 mL of nutrient solution. Following each leaching, Parafilm® was used to cover leachate test tubes to prevent contamination and to preserve soil water content during this study. Air vents were created in the parafilm to allow for

air exchange. At the end of the leaching period, leachate was collected, covered and refrigerated (8-24 hours) if necessary, until mineral N analysis was conducted using a Timberline TL 2900 NH<sub>4</sub>/NO<sub>3</sub> analyzer (Timberline Instruments Inc., Boulder, CO). Leaching tubes were then transferred into the freezer for three weeks at -5°C. After the freeze period, the soils were thawed and incubations were repeated.

# 5.3.2. Statistical Analysis

The Analysis of Variance (ANOVA) model was fitted with GLIMMIX procedure to determine the effects of crop residue treatment, incubation series, leaching period, and their interactions on NO<sub>3</sub>-N mineralization. As the measurements of NO<sub>3</sub>-N mineralization collected from same experimental tube unit are correlated over time, the model was connected by imposing certain covariance structure on the error term of the model. Akaike's Information Criteria (AIC) was used to determine the appropriate covariance structure and the smaller AIC value the better. Throughout this study, AR(1) covariance structure was always producing smaller AIC value. The Least Square mean (LS-mean) of each level of cycle was estimated and the significance of the difference between all possible pairs of these LS-means was identified with Tukey's Honest Significant Difference (HSD) at significant level of 0.05. In addition, LSmean of each level of crop residual treatment within each incubation series, was estimated and HSD test with significant level of 0.05 was performed to test the significant difference among all possible pairs of the LS-means. Moreover, LS-mean of each level of crop residue treatment for each leaching period (day) within each incubation series was estimated and HSD test with significant level of 0.05 was used to find the LS-means that are significantly different from each other.

The study shows that radish (R-R-R) crop residue always produced larger amount of NO<sub>3</sub>-N mineralization than other crop residue treatments, in order to test whether the significant effect of crop residue treatments on the NO<sub>3</sub>-N mineralization was due to radish (R-R-R) only, same analyses mentioned above were also performed with data excluding measurements from radish (R-R-R) crop residue. The radish (R-R-R) treatment was used as a second control against other crop residue treatments to compare the crop residue rotations with radish additions. All analyses were conducted by SAS version 9.4 (SAS Institute, 2013).

## 5.4. Results and Discussion

Incubation means of soil NO<sub>3</sub>-N mineralization for the mixed crop residue treatments with and without cover crop show an occurrence of immobilization regardless of their rotations following the second incubation (following the first freeze and thaw cycle). Whereas incubation mean soil NO<sub>3</sub>-N mineralization in the first and third incubations are significantly different from the results of the second incubation (Table 7). The overall differences in the means observed can be attributed to the increased NO<sub>3</sub>-N mineralization provided by the radish cover crop treatment which skewed overall means for incubation one and three. Crop residue diversification did not mitigate NO<sub>3</sub>-N immobilization trends over all incubations and leaching periods with a few exceptions (n=5) where the three-year rotation with radish was mineralizing above the soil alone, but not significantly different from it.

Figure 25 shows the mineralization characteristics of the twelve crop residue treatments and rotations relative to the mineralization of the untreated, bare soil control during the first incubation series (following the first growing season). The untreated, bare soil is represented by the horizontal line with N mineralization indicated as positive values above the line and N immobilization indicated as negative values below the line. Values on the line indicate that no

net N mineralization or immobilization were occurring for the particular crop residue treatment and rotation or that date (a neutral N situation) relative to N mineralization by the soil.

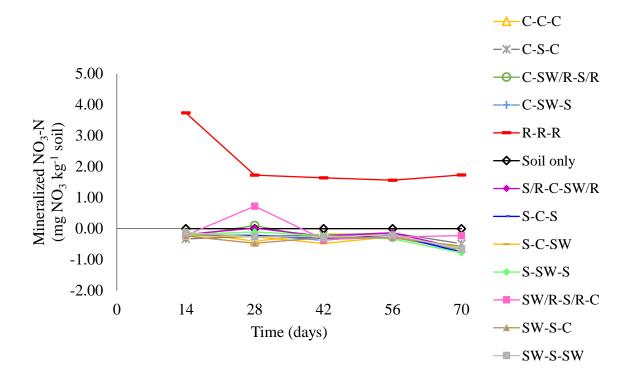


Figure 25. Mineralization and immobilization of NO<sub>3</sub>-N for the first simulated cropping season for twelve crop residue treatments and their rotations for corn (C), soybean (S), spring wheat (SW), and radish (R), plus an untreated, bare soil control for the Forman soil series in North Dakota.

Based on Figure 25, it is evident that radish by itself is the only crop residue showing clear net NO<sub>3</sub>-N mineralization during the first simulated growing season. The SW/R-S/R-C (containing 15% radish) in this part of the rotation shows a peak in net mineralization during the second leaching at day 28 and slight uptick at day 70. The S/R-C-SW/R (containing 15% radish) in this part of the rotation shows a peak in net mineralization during the second leaching at day 28 then quickly shows immobilization trends. When further examining these means, it becomes clear that the values are out of the upper and lower ranges of the data (Figure 26).

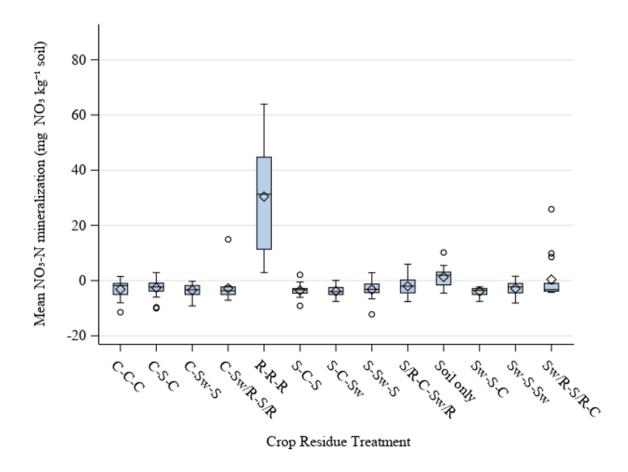


Figure 26. NO<sub>3</sub>-N mineralization mean box plots for the first simulated cropping season for twelve crop residue treatments and their rotations for corn (C), soybean (S), spring wheat (SW), and radish (R), plus an untreated, bare soil control for the Forman soil series in North Dakota.

Figure 27 shows the mineralization characteristics of the twelve crop residue treatments and rotations relative to the mineralization of the untreated, bare soil control after the first freeze and thaw cycle (second growing season). Again, it is evident that radish by itself is the only crop residue showing net NO<sub>3</sub>-N mineralization for the series and an increase in NO<sub>3</sub>-N mineralization over the first cropping season is also evident for the radish series over series. This is the only crop residue to exhibit such a pattern. Soybean and spring wheat residues combined with 15% radish residue treatment did not show an effective offset in N immobilization during this incubation although treatments with radish do show slightly higher values (though not significantly different) than rotations without a cover crop.

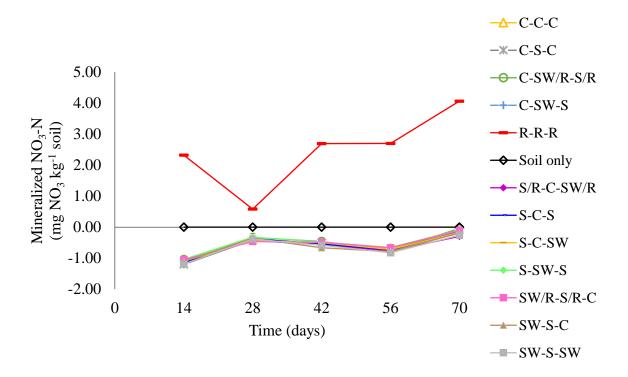


Figure 27. Mineralization and immobilization of NO<sub>3</sub>-N for the second simulated cropping season for twelve crop residue treatments and their rotations for corn (C), soybean (S), spring wheat (SW), and radish (R), plus an untreated soil control for the Forman soil series in North Dakota. N mineralization of the soil is represented by values above the line, while N immobilization is represented by values below the line.

Figure 28 shows the third incubation series mineralization characteristics of the twelve crop residue treatments and rotations relative to the mineralization of the untreated, bare soil control after the second freeze and thaw cycle (third growing season). Radish, again, exhibits the only net NO<sub>3</sub>-N mineralization potential that is consistent throughout the entire growing season. In this incubation series, the S/R-C-SW/R, SW/R-S/R-C, SW-S-C, and SW-S-SW rotations indicate some net NO<sub>3</sub>-N mineralization at the day 14 NO<sub>3</sub>-N measurement.

Table 7. Mean and cumulative NO<sub>3</sub>-N mineralization over three incubation periods with five leaching periods and two freeze and thaw cycles for corn (C), radish (R), soybean (S), and spring wheat (SW) crop residues for the Forman soil series in North Dakota.

		Nitrogen mineralization per leaching period (days), mg NO <sub>3</sub> kg <sup>-1</sup>							
Incubation	Crop Residue Treatment	1 <sup>st</sup> (14 d.)	2 <sup>nd</sup> (28 d.)	3 <sup>rd</sup> (42 d.)	4 <sup>th</sup> (56 d.)	5 <sup>th</sup> (70 d.)	Cumulative	Overall Mean§	Incubation Mean ¶
1 <sup>st</sup>	Soil only <sup>†</sup>	-0.171b <sup>‡</sup>	0.977b	1.298b	0.806b	3.708b	6.618b	$1.34b \pm 3.73$	0.056a
	<u>C</u> -C-C	-1.712b	-4.701b	-1.027b	-2.054b	-6.161b	-15.655b	$-3.34b \pm 3.39$	
	<u>C</u> -S-C	-4.792b	-2.482b	-1.626b	-1.113b	-3.081b	-13.094b	$-2.70b \pm 3.77$	
	<u>S</u> -C-S	-3.423b	-2.139b	-3.166b	-2.054b	-6.932b	-17.714b	$-3.62b \pm 2.50$	
	<u>SW</u> -S-SW	-1.883b	-2.653b	-1.883b	-2.054b	-5.391b	-13.864b	$-2.91b \pm 2.95$	
	<u>S</u> -SW-S	-2.824b	-0.513b	-1.883b	-3.851b	-7.188b	-16.259b	$-3.34b \pm 3.45$	
	<u>SW</u> -S-C	-3.509b	-5.648b	-2.738b	-3.337b	-4.193b	-19.425b	$-3.88b \pm 1.42$	
	S-C-SW	-3.337b	-2.653b	-5.391b	-2.824b	-4.878b	-19.083b	$-3.83b \pm 2.02$	
	C-SW-S	-3.081b	-1.883b	-4.020b	-1.626b	-6.675b	-17.285b	$-3.53b \pm 2.31$	
	SW/R-S/R-C	-3.252b	11.13ab	-3.594b	-2.995b	5.599b	6.888b	$0.29b \pm 8.32$	
	S/R-C-SW/R	-2.824b	1.198b	-2.139b	-1.037b	-5.391b	-10.193b	$-2.12b \pm 3.44$	
	C-SW/R-S/R	-3.680b	2.396b	-3.509b	-3.081b	-6.076b	-13.95b	$-2.89b \pm 5.15$	
	<u>R</u> -R-R	52.12a	25.16a	24.217a	22.68a	27.983a	152.16a	$30.9a\pm17.8$	
$2^{nd}$	Soil only	5.855b	1.063b	1.891b	3.282b	-0.354b	11.737b	$2.31b \pm 5.72$	-1.986b
	C- <u>C</u> -C	-10.97bc	-4.664b	-6.033b	-6.03bc	-2.867b	-30.56bc	$-5.2bc \pm 3.60$	
	C- <u>S</u> -C	-10.996c	-4.706b	-5.776b	-6.76bc	-3.124b	-31.356bc	$-5.95c \pm 2.83$	
	S- <u>C</u> -S	-10.26bc	-4.193b	-5.691b	-6.93bc	-2.439b	-29.513bc	$-5.5$ bc $\pm 3.04$	
	SW- <u>S</u> -SW	-10.782c	-4.364b	-6.247b	-8.26c	-4.022b	-33.675bc	$-6.65c \pm 2.92$	
	S-SW-S	-8.729bc	-3.466b	-4.878b	-5.91bc	-1.668b	-24.65bc	$-4.6bc \pm 2.90$	
	SW- <u>S</u> -C	-9.669bc	-3.936b	-7.445b	-7.79bc	-2.995b	-31.835c	$-6.04c \pm 2.87$	
	S-C-SW	-9.542bc	-5.049b	-5.092b	-6.80bc	-2.653b	-29.139bc	$-5.6bc \pm 2.44$	
	C- <u>SW</u> -S	-9.969bc	-4.193b	-6.033b	-7.23bc	-2.995b	-30.42c	$-5.98c \pm 2.67$	
	SW/R-S/R-C	-8.899bc	-5.391b	-4.963b	-6.03bc	0.984b	-24.299bc	$-4.8bc \pm 3.12$	
	S/R- <u>C</u> -SW/R	-9.969bc	-4.963b	-5.947b	-7.45bc	-4.535b	-32.864c	$-6.02c \pm 2.70$	
	C-SW/R-S/R	-8.771bc	-3.637b	-4.578b	-7.14bc	-0.984b	-25.11bc	$-5.3bc \pm 3.02$	
	R-R-R	38.379a	9.199a	39.578a	41.032a	56.52a	184.708a	$37.9a \pm 20.2$	
$3^{rd}$	Soil only	0.214b	3.266b	1.041b	1.583b	1.227b	7.331b	$1.30b \pm 3.38$	1.436a
	C-C- <u>C</u>	-1.883b	-1.498b	-5.092b	-5.520b	-2.054b	-16.047b	$-3.03b \pm 1.94$	
	C-S- <u>C</u>	-1.712b	2.353b	-4.236b	-3.936b	-3.081b	-10.612b	$-2.04b \pm 2.94$	
	S-C- <u>S</u>	-0.171b	-1.412b	-2.067b	-4.878b	-3.680b	-12.208b	$-0.76b \pm 2.85$	
	SW-S- <u>SW</u>	1.669b	-0.342b	-1.498b	-2.439b	-3.765b	-6.375b	$-0.98b \pm 3.72$	
	S-SW- <u>S</u>	-3.295b	-1.128b	-4.963b	-3.851b	-3.380b	-16.617b	$-3.11b \pm 2.22$	
	SW-S-C	2.011b	-1.754b	-5.477b	-4.150b	-3.337b	-12.707b	$-1.42b \pm 3.61$	
	S-C- <u>SW</u>	-1.155b	0.020b	-4.493b	-5.006b	-0.984b	-11.618b	$-2.16b \pm 2.59$	
	C-SW- <u>S</u>	-2.396b	-2.696b	-5.348b	-5.562b	-4.065b	-20.067b	$-3.45b \pm 1.67$	
	SW/R-S/R- <u>C</u>	4.236b	-0.342b	-3.081b	-3.680b	-3.894b	-6.761b	$0.55b \pm 4.11$	
	S/R-C- <u>SW/R</u>	1.883b	0.385b	-3.509b	-2.353b	-1.840b	-5.434b	$-0.72b \pm 2.62$	
	C-SW/R- <u>S/R</u>	-2.867b	-1.540b	-4.193b	-1.626b	-2.781b	-13.007b	$-1.54b \pm 2.05$	
	R-R-R	59.388a	51.087a	40.348a	39.321a	26.357a	216.501a	$40.1a \pm 20.9$	

<sup>†</sup>Underlined crop residue(s) indicate the current crops(s) represented in the incubation cycle

Different letters within a column are significantly different for each incubation cycle at the 0.05 level using Tukey's HSD test.

<sup>§</sup> Nitrogen mineralization mean over all incubation periods for each crop residue treatment.

Nitrogen mineralization mean over all incubation periods including all crop residue treatments.

This is the same time period where radish reaches peak mineralization (early in the growing season), though mineralization tails throughout the incubation series for the R-R-R (continuous radish application for the three cropping cycles – used as a second control treatment) and may indicate lack of diversity in new organic matter substrate in the radish material alone.

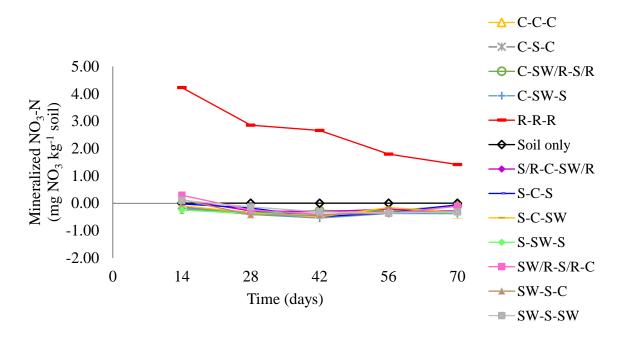


Figure 28. Mineralization and immobilization of NO<sub>3</sub>-N for the third simulated cropping season for twelve crop residue treatments and their rotations for corn (C), soybean (S), spring wheat (SW), and radish (R), plus an untreated soil control for the Forman soil series in North Dakota. N mineralization of the soil is represented by values above the line, while N immobilization is represented by values below the line.

A possible reason for the mineralization patterns observed is the C:N ratios of the crop residue treatments (Aher et al., 2016). High C:N ratios (C:N > 40) such as corn (C:N = 57), soybean (C:N = 70), and spring wheat (C:N = 43) do not demonstrate a dynamic N mineralization trend over a period of time that represents critical nutrient needs period of most crops requiring N in North Dakota. Over the three incubation series (growing seasons), these crop residues and their rotations are relatively neutral at supplying crop N needs. Low C:N crop residue, such as radish (C:N = 11.8) does appear to provide N crop needs by itself, but not for all

rotations where it is incorporated with soybean or spring wheat residues. A primary reasoning for the absence of NO<sub>3</sub>-N mineralization trends for all rotations with radish is that the radish biomass is only a small part of the total biomass common with corn, soybean, and wheat systems in North Dakota. Other studies have indicated similar findings and concluded that the additional of a cover crop into a cropping system rotation may not provide adequate NO<sub>3</sub>-N to subsequent crops when needed; therefore, an N credit may not be warranted (Vyn et al., 2000; Moller and Reents, 2009; O'Reilly et al., 2012; Li et al., 2015; Lacey and Armstrong, 2015; Gieske et al., 2016; Hill et al., 2016; Ruark et al., 2018).

As the no-till system matures (series over series) there does appear to be an effect as more crop residues and their rotations near either values of the untreated soil or possibly achieve slight amounts of N mineralization at some point during the incubation series. This may also be attributed to the freeze and thaw effects. Other studies have demonstrated the influence of freezing and thawing on both NO<sub>3</sub>-N tie up and release as compared to wet and dry cycles (Shields et al., 1974). Freeze and thaw cycles expand and disturb the soil which aids in breaking up soil aggregates, exposing protected residue to soil microbes where they will feed on residue (Rovira and Greacen, 1957; Gasser, 1958; Soulides and Allison, 1961; Witkamp, 1969; Ivarson and Sowden, 1970; Ross, 1972).

# 5.5. Conclusion

This examination of mixed crop residues incorporated with and without a cover crop helps one better understand N mineralization dynamics in a no-till cropping system where residue accumulates season over season. Based on the findings from this study, incorporating narrow C:N ratio cover crops such as radish with other wider C:N ratio crops in a rotation component of the cropping system did not facilitate N mineralization nor did it offset N

immobilization by wide C:N ratio crops. The only crop residue treatment and/or rotation that shows N mineralization was the radish alone while other crop residue treatments and/or their rotations show immobilization patterns. In this research, crop residue diversification with twoyear and three-year rotations, and three-year rotations plus cover crop did not ultimately result in N mineralization. However, there were some occasions where crop residue showed the potential for mineralization, but only for the three-year rotations with cover crop. When these occurrences were evidence, there presence occurred in the early growing season (Day 14). Thus, this leads one to conclude that incorporating cover crop in a cool environment has the potential to mitigate net N immobilization, though would need to be confirmed in a field setting. The occurrence of freeze and thaw cycles can potentially help release nutrients back to the soil. Under North Dakota climatic conditions, freeze and thaw cycles may have a stimulation effect on soil N mineralization for crops with a wide C:N ratio. However, this needs to be verified by other studies. Future research may consider incorporating an untreated, bare soil control with crop residues treatments and their rotations with no freeze and thaw conditions to observe any variances from our findings.

The narrow C:N ratio of the radish cover crop may help offset higher biomass quantity of non-cover crops in the rotation but may not provide adequate enhanced benefits of N mineralization to the system. However, mineralization of NO<sub>3</sub>-N may be enhanced with additional N fertilizer. In this study, the addition of radish cover crop residue at 15% of total biomass did aid in NO<sub>3</sub>-N mineralization for succeeding crops in three-year rotations early in the growing season, though only in the third growing season. Further field studies would be helpful to understand the effect of incorporating diversified, common cropping systems in the region with varying rates (> 15%) of common N-accumulating cover crops. A higher rate of cover crop

residue incorporation into the common cropping systems in North Dakota may facilitate the substrate availability to microorganisms where NO<sub>3</sub>-N will not be limited to plants or microorganisms, thus resulting in a net N mineralization effect. After harvest, the relative amounts of biomass remaining of each crop type may have equally important impact on plant availability of N as the C:N ratio of the material.

# 5.6. References

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## 6. SUMMARY OF RESEARCH FINDINGS

These long-term incubation studies aid in providing a picture of the nitrogen mineralization potential and nitrogen immobilization trends for common individual crop residue, mixed crop residues, and crop residue and freeze and thaw effects on decomposition from diversified cropping systems in the frigid climate of North Dakota. The purpose of this research was to provide insights to determine whether the quantity of crop residue remaining on the soil surface in a long-term no-till system provides nitrogen to subsequent crops when needed the most. Climatic conditions, such as moisture and temperature, are among the decomposition factors to consider with crop residue. In North Dakota, the climatic environment with cool temperatures averaging 5°C coupled with short growing seasons (100-135 frost free days), and unpredictable wet and dry cycles presents unique management challenges for farmers. In the region, there has been a shift in agricultural production from small grains, sunflower (Helianthus L.), and barley (Hordeum vulgare L.) to corn (Zea mays L.) and soybean (Glycine max L.) (Kaur et al., 2018). Corn alone has experienced a six-fold increase in yields in the Midwestern U.S. since the 1930s (Triplett and Dick, 2008). In addition to agricultural production changes, management of the land has also evolved from frequent deep tillage to conservation tillage. With these changes, a greater volume of crop residue can now be found on the soil surface. One thing that remains consistent, is a crop's requirement for adequate soil supplied nutrients for optimum growth and the farmer's reliance on fertilizers for primary production. With the most common limiting nutrient being nitrogen; environmentalists are also interested in further understanding nitrogen dynamics to limit non-point source pollution from agricultural environments. Nitrogen transformations and plant responses are complex and thus both agriculturists and environmentalists must work together to better understand needs of the nation for now and into the future.

Under a no-till system, cases of decreased nitrogen uptake (immobilization) are often reported (McConkey et al., 1996; Kaur et al., 2018). In many cases, the differences in C:N ratios have been cited as a primary crop residue decomposition factor (Mendham et al., 2004; Muhammad et al., 2011; Kaur et al., 2018). In a no-till system, a higher C:N ratio has been documented in plant residues on or near the soil surface and subsequent N immobilization has been observed where microbes compete for N and energy sources (Allison, 1973; Doran, 1980; Doran, 1987; Havlin et al., 2005). Several states in the northern U.S. with cool climates have recommended N fertilizer additions above crop needs in long-term no-till systems to offset immobilization (Bundy, 1998; Ketterings et al., 2003; Jokela et al., 2004; Dinkins and Jones, 2019). Current N recommendations by North Dakota State University are to provide a 22 kg N ha<sup>-1</sup> credit for no-till systems of 5 years or less and a 34 kg N ha<sup>-1</sup> credit for N-till systems of 6 years or greater (Franzen, 2018). For the last ten years, recommendations for the state of North Dakota have frequently changed.

In North Dakota, producers have questioned if nitrogen is mineralizing from a heavy accumulation of residue or not. Others have extended this question to a review of current fertilizer N recommendations in the state citing necessity of site-specific characteristics in recommendations (Chatterjee et al., 2018). With a range of conservation tillage practices widely adopted across the region, it becomes important for farmers to have a better understanding of complimentary N fertilizer best management practices for resource optimization (modifying N credits for optimal system and plant productivity). This research was designed to provide the data needed to support the recommendation and/or modifications for current N credits in North Dakota.

Experiment 1 (Chapter 3) demonstrated a net N immobilization effect for corn, soybean, spring wheat, and winter wheat residue over eighteen weeks of lab incubation using simulated long-term conventional tillage systems where residue was incorporated below the soil surface. An observation of immobilization of NO<sub>3</sub>-N from non-leguminous crop residue is consistently observed in our results across all soil series (Heimdal-Emrick, Fargo, and Forman). This research also noticed differences in the cumulative mineralization due to soil texture for the Heimdal-Emrick, Fargo, and Forman soil series. Greater cumulative mineralization for the Fargo soil series was observed and attributed to its texture, water holding capacity, and organic matter content. Experiment 2 (Chapter 4) examined the question if that annual freeze and thaw cycles may accelerate mineralization of non-leguminous crop residue from long-term no-till systems. Findings suggest that there is a possible impact of freeze and thaw cycles on N mineralization, but only cover crops with a narrow C:N ratio crop residue (forage radish and winter pea) showed consistent net N mineralization and was observed in the period corresponding to the mid to late growing season. Overall, the accumulation of crop residue on top of soil surface as compared to incorporation below the soil surface (in Chapter 3) did not increase soil mineralized NO<sub>3</sub>-N. Experiment 3 (Chapter 5) more closely defined the mineralization and immobilization response of NO<sub>3</sub>-N in a long-term no-till system with varying crop rotations, more closely aligned with conditions in a field setting and the potential for utilizing NO<sub>3</sub>-N rich cover crops to offset the N immobilization by high C:N ratio crop residue observed in Chapter 3 and 4. Findings suggest that, in general, incorporating a narrow C:N ratio cover crop (forage radish) with wider C:N ratio crops in a rotation component of the cropping system did not provide a significant offset of N immobilization by the wide C:N ratio crops. There were a few occasions where the addition of the radish cover crop residue did aid in N mineralization for succeeding crops in the three-year

rotations early in the growing season, though this only occurred in the third growing season but may illustrate the positive cumulative effect of including N scavenging cover crop at appropriate points in a cropping system.

Overall, findings of these experiments show that most wide C:N ratio crop residues will immobilize soil N in a no-till system under ideal conditions (i.e. moisture, temperature, and residue particle size). Incorporating a cover crop in a cool environment has the potential to stimulate soil N mineralization, though would need to be confirmed in a field setting at varying rates of residue application. In the literature, others with similar soils and climates have concluded that although cover crops may provide initial NO<sub>3</sub>-N benefits, they may not be an adequate substitute for fertilizer application, and N mineralization alone may not be enough to award a credit for the following crop season (Vyn et al., 2000; O'Reilly et al., 2012; Li et al., 2015; Lacey and Armstrong, 2015; Gieske et al., 2016; Hill et al., 2016; Ruark et al., 2018).

In a field setting, it is expected that residue remaining on the soil surface would decompose much slower than that observed in a laboratory setting because of the lower total surface area available for decomposing soil microorganisms to act on. Mineralization of NO<sub>3</sub>-N may be enhanced with additional N fertilizer but further detailed studies are required to confirm this. Fertilizer derived N would supply that which is needed by the microorganisms to be able to function in a way that provide enough N for optimum crop yield and protein quality. In general, however, recommendations in North Dakota have failed to take soil moisture into consideration when making recommendations, though previous studies in the region have documented the importance in relationship between soil nitrate and soil moisture (Bauer 1965; Reichman et al., 1966; Power, 1967; Young et al., 1967; Power, 1968; Power and Alessi, 1971; Swenson et al.,1979). These experiments were conducted in a lab-controlled environment where moisture

and temperature were kept constant. One of the advantages of no-till cropping systems is that they conserve soil moisture in regions of limited rainfall. A main component of plant growth is water availability. A favorable crop response to N fertilizers observed in no-till cropping systems could be due to water availability alone making plant N use more efficient. The research conducted here suggests that North Dakota N fertilizer recommendations should be re-evaluated for long-term no-till systems taking into consideration soil moisture with validated data to support the N credit or lack thereof.

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## **APPENDIX**

## A.1. Additional Tables

Table A1. Mean and cumulative NH<sub>4</sub>-N mineralization for nine incubation periods and overall mean for corn, flax, pea, radish, soybean, spring wheat, and winter wheat crop residues for Heimdal-Emrick, Fargo, and Forman soil series in North Dakota.

		Nitrogen mineralization per leaching incubation period (days), mg NH <sub>4</sub> kg <sup>-1</sup>										
Soil	Crop Residue	1 <sup>st</sup>	$2^{\text{nd}}$	3 <sup>rd</sup>	4 <sup>th</sup>	5 <sup>th</sup>	6 <sup>th</sup>	$7^{\rm th}$	8 <sup>th</sup>	9 <sup>th</sup>	Cumulative	Overall Mean <sup>±</sup>
Series	Treatment	(14 d.)	(28 d.)	(42 d.)	(56 d.)	(70 d.)	(84 d.)	(98 d.)	(112 d.)	(126 d.)		
Heimdal-	Soil only	$0.054b^{\dagger}$	0.210b	1.20b	3.867bc	2.457b	2.456a	1.473ab	0.853ab	0.848a	13.3bc	$1.48bc \pm 1.52$
Emrick	Corn	0.000b	0.000b	0.000b	0.000c	0.000b	0.254a	0.001b	0.000b	0.000a	1.137c	$0.126c \pm 0.30$
	Flax	0.000b	0.000b	0.000b	0.000c	0.000b	1.423a	2.408ab	1.431ab	0.000a	6.45bc	$0.71bc \pm 1.22$
	Pea	0.000b	3.126b	5.316ab	7.178b	3.785ab	3.059a	1.345ab	0.426b	0.000a	25.11b	$2.790b \pm 3.01$
	Radish	4.754a	12.903a	13.795a	13.864a	7.792a	5.836a	5.569a	4.820a	1.773a	71.11a	$7.901a \pm 5.94$
	Soybean	0.000b	0.000b	0.000b	0.559c	0.358b	0.268a	0.314b	0.000b	0.740a	2.240c	$0.249c \pm 0.41$
	Spring Wheat	0.000b	0.147b	0.000b	0.000c	0.000b	3.681a	0.000b	0.000b	0.000a	4.671c	$0.519c \pm 2.11$
	Winter Wheat	0.000b	0.000b	0.000b	0.000c	0.000b	0.047a	0.237b	0.000b	0.000a	1.120c	$0.124c \pm 0.29$
Fargo	Soil only	11.082b	9.472b	4.939b	2.999b	2.005b	1.250b	7.265a	1.942a	1.942b	40.95c	$4.876c \pm 4.81$
8	Corn	0.000b	0.000c	0.000b	0.000b	0.000b	0.395b	0.000b	0.000a	0.000b	1.392c	$0.135c \pm 0.35$
	Flax	0.000b	0.000c	0.000b	0.000b	0.000b	1.758b	0.000b	0.015a	0.000b	2.655c	$0.304c \pm 0.86$
	Pea	0.000b	14.671b	30.693a	21.133a	12.338a	9.682ab	0.299ab	0.510a	0.000b	101.8b	$12.48b \pm 11.4$
	Radish	30.979a	26.749a	44.407a	32.800a	18.049a	19.814a	0.000b	2.520a	5.894a	181.2a	$21.91a \pm 16.6$
	Soybean	0.000b	0.000c	0.000b	0.947b	0.481b	0.444b	0.000b	0.000a	0.321b	4.059c	$0.467c \pm 0.92$
	Spring Wheat	0.000b	0.000c	0.000b	0.000b	0.000b	0.000b	0.000ab	0.000a	0.000b	0.622c	$0.056c \pm 0.35$
	Winter Wheat	0.000b	0.000c	0.000b	0.000b	0.000b	0.000b	1.789ab	0.000a	0.000b	3.915c	$0.451c \pm 1.11$
Forman	Soil only	11.082b	9.472b	4.939b	2.999b	2.005b	1.250b	7.265a	0.000a	0.800a	39.81b	$0.000b \pm 0.18$
	Corn	0.000b	0.000c	0.000b	0.000b	0.000b	0.395b	0.000b	0.000a	0.000a	1.813b	$0.086b \pm 0.44$
	Flax	0.000b	0.000c	0.000b	0.000b	0.000b	1.758b	0.000b	0.015a	0.000a	3.045b	$0.000b \pm 0.20$
	Pea	0.000b	14.671b	30.693a	21.133a	12.338a	9.682ab	0.2987ab	0.51a	0.000a	100.5b	$0.856b \pm 1.67$
	Radish	30.979a	26.749a	44.407a	32.800a	18.049a	19.814a	0.000b	2.520a	2.180a	177.4a	$2.689a \pm 3.29$
	Soybean	0.000b	0.000c	0.000b	0.947b	0.481b	0.444b	0.000b	0.000a	0.850a	4.588b	$0.079b \pm 0.34$
	Spring Wheat	0.000b	0.000c	0.000b	0.000b	0.000b	0.000b	0.000ab	0.000a	0.000a	1.240b	$0.000b \pm 0.13$
<del>+</del>	Winter Wheat	0.000b	0.000c	0.000b	0.000b	0.000b	0.000b	1.789ab	0.000a	0.000a	4.490b	$0.000b \pm 0.15$

<sup>†</sup>Different letters within a column for each soil series are significantly different at the 0.05 level using Tukey's HSD test. 
<sup>±</sup> Nitrogen mineralization mean over all incubation periods for each crop residue within individual soil series.

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Table A2. Analysis of variance P-value table for NH<sub>4</sub>-N mineralization per crop residue treatment analyzed for fixed effect of leaching incubation period and soil texture.

					reatment P-valu					
Soil Series	Incubation (Days)	Soil only	Corn	Flax	Pea	Radish	Soybean	Spring Wheat	Winter Wheat	Overall <sup>±</sup>
Heimdal-	1 <sup>st</sup> (14 d.)	0.921	1.000	1.000	1.000	< 0.0001	1.000	1.000	1.000	< 0.0001
Emrick	2 <sup>nd</sup> (28 d.)	0.879	1.000	1.000	0.035	< 0.0001	1.000	0.915	1.000	< 0.0001
	3 <sup>rd</sup> (42 d.)	0.547	1.000	1.000	0.010	< 0.0001	1.000	1.000	1.000	0.001
	4 <sup>th</sup> (56 d.)	0.006	1.000	1.000	< 0.0001	< 0.0001	0.653	1.000	1.000	< 0.0001
	5 <sup>th</sup> (70 d.)	0.023	1.000	1.000	0.001	< 0.0001	0.718	1.000	1.000	0.001
	6 <sup>th</sup> (84 d.)	0.246	0.902	0.495	0.153	0.011	0.897	0.090	0.982	0.470
	7 <sup>th</sup> (98 d.)	0.119	0.999	0.016	0.152	< 0.0001	0.730	1.000	0.794	0.007
	8 <sup>th</sup> (112 d.)	0.327	1.000	0.109	0.620	< 0.0001	1.000	1.000	1.000	0.012
	9 <sup>th</sup> (126 d.)	0.006	0.004	0.001	0.005	< 0.0001	0.013	0.006	0.006	0.201
Fargo	1 <sup>st</sup> (14 d.)	0.005	0.934	0.959	0.007	< 0.0001	0.747	1.000	0.916	< 0.0001
	2 <sup>nd</sup> (28 d.)	< 0.0001	1.000	1.000	< 0.0001	< 0.0001	1.000	1.000	1.000	< 0.0001
	3 <sup>rd</sup> (42 d.)	0.259	0.990	0.912	< 0.0001	< 0.0001	1.000	1.000	0.956	< 0.0001
	4th (56 d.)	0.264	0.986	1.000	< 0.0001	< 0.0001	0.719	1.000	0.726	< 0.0001
	5 <sup>th</sup> (70 d.)	0.232	1.000	1.000	< 0.0001	< 0.0001	0.770	1.000	1.000	< 0.0001
	6 <sup>th</sup> (84 d.)	0.617	0.874	0.483	0.001	< 0.0001	0.858	1.000	1.000	0.001
	7 <sup>th</sup> (98 d.)	0.001	1.000	1.000	0.839	1.000	1.000	0.761	0.234	0.032
	8 <sup>th</sup> (112 d.)	1.000	0.756	0.988	0.602	0.018	0.449	1.000	0.761	0.622
	9 <sup>th</sup> (126 d.)	0.089	0.115	0.180	0.112	0.001	0.070	0.089	0.062	0.300
Forman	1 <sup>st</sup> (14 d.)	1.000	0.258	1.000	1.000	< 0.0001	1.000	1.000	1.000	< 0.0001
	2 <sup>nd</sup> (28 d.)	1.000	1.000	1.000	0.592	< 0.0001	0.910	1.000	1.000	0.014
	3 <sup>rd</sup> (42 d.)	1.000	1.000	1.000	0.466	0.001	1.000	1.000	1.000	0.052
	4 <sup>th</sup> (56 d.)	1.000	1.000	1.000	0.082	0.004	0.662	1.000	1.000	0.227
	5 <sup>th</sup> (70 d.)	1.000	1.000	1.000	0.024	0.197	1.000	1.000	1.000	0.543
	6 <sup>th</sup> (84 d.)	1.000	1.000	1.000	0.024	0.204	1.000	1.000	1.000	0.542
	7 <sup>th</sup> (98 d.)	1.000	1.000	1.000	0.030	0.145	1.000	1.000	1.000	0.550
	8 <sup>th</sup> (112 d.)	1.000	1.000	1.000	0.742	0.192	1.000	1.000	1.000	0.519
	9 <sup>th</sup> (126 d.)	1.000	1.000	1.000	0.525	0.312	1.000	1.000	1.000	0.488

<sup>\*</sup> Nitrogen mineralization significance over all incubation periods for each crop residue within individual soil series.

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Table A3. Analysis of variance P-value table for  $NO_3$ -N mineralization per crop residue treatment analyzed for fixed effect of leaching incubation period and soil texture.

	-		Cro	p Residue Tre	atment P-value					
Soil Series	Incubation (Days)	Soil only	Corn	Flax	Pea	Radish	Soybean	Spring Wheat	Winter Wheat	Overall <sup>±</sup>
Heimdal-	1 <sup>st</sup> (14 d.)	< 0.0001	0.141	0.651	0.921	< 0.0001	1.000	0.237	1.000	< 0.0001
Emrick	2 <sup>nd</sup> (28 d.)	< 0.0001	0.787	1.000	0.122	0.001	0.852	0.993	0.971	0.001
	3 <sup>rd</sup> (42 d.)	0.034	1.000	1.000	0.001	< 0.0001	0.793	0.896	1.000	< 0.0001
	4 <sup>th</sup> (56 d.)	0.002	0.780	0.582	0.001	< 0.0001	0.020	0.635	0.605	0.001
	5 <sup>th</sup> (70 d.)	0.014	0.934	0.756	0.036	< 0.0001	0.359	0.891	0.994	0.011
	6 <sup>th</sup> (84 d.)	0.049	0.357	0.281	0.008	0.004	0.223	0.004	0.416	0.354
	7 <sup>th</sup> (98 d.)	< 0.0001	0.027	0.001	< 0.0001	< 0.0001	0.001	0.057	0.054	0.013
	8 <sup>th</sup> (112 d.)	0.001	0.126	0.053	0.089	< 0.0001	0.161	0.421	0.312	0.061
	9 <sup>th</sup> (126 d.)	< 0.0001	1.000	1.000	1.000	< 0.0001	0.827	1.000	1.000	< 0.0001
Fargo	1 <sup>st</sup> (14 d.)	0.001	0.465	0.594	0.001	< 0.0001	0.447	0.675	0.473	< 0.0001
C	2 <sup>nd</sup> (28 d.)	0.001	0.954	0.997	0.001	< 0.0001	0.980	0.950	0.929	0.001
	3 <sup>rd</sup> (42 d.)	< 0.0001	0.919	0.920	< 0.0001	< 0.0001	0.930	0.894	0.899	< 0.0001
	4 <sup>th</sup> (56 d.)	0.001	0.799	0.982	< 0.0001	< 0.0001	0.674	0.915	0.701	0.001
	5 <sup>th</sup> (70 d.)	0.093	0.946	0.807	< 0.0001	< 0.0001	0.589	0.904	0.843	0.001
	6 <sup>th</sup> (84 d.)	0.428	0.888	0.863	0.018	0.001	0.877	0.933	0.922	0.032
	7 <sup>th</sup> (98 d.)	0.045	0.790	0.832	0.880	0.873	0.943	0.022	0.917	0.442
	8 <sup>th</sup> (112 d.)	0.501	0.890	0.812	0.210	< 0.0001	0.737	0.973	0.923	0.007
	9 <sup>th</sup> (126 d.)	0.675	0.970	0.932	0.688	< 0.0001	0.873	1.000	1.000	0.016
Forman	1st (14 d.)	0.008	0.701	0.732	0.003	< 0.0001	0.988	0.775	0.912	< 0.0001
	2 <sup>nd</sup> (28 d.)	0.025	1.000	0.972	0.006	0.002	0.950	0.989	0.969	0.053
	3 <sup>rd</sup> (42 d.)	0.001	0.957	0.872	0.001	< 0.0001	0.668	0.857	0.920	0.001
	4 <sup>th</sup> (56 d.)	< 0.0001	0.988	0.834	< 0.0001	< 0.0001	0.304	0.856	0.598	0.001
	5 <sup>th</sup> (70 d.)	< 0.0001	0.882	1.000	< 0.0001	< 0.0001	0.496	1.000	1.000	< 0.0001
	6 <sup>th</sup> (84 d.)	< 0.0001	0.641	0.185	< 0.0001	< 0.0001	0.228	0.373	0.123	0.001
	7 <sup>th</sup> (98 d.)	< 0.0001	0.335	0.045	0.001	< 0.0001	0.090	0.069	0.099	< 0.0001
	8 <sup>th</sup> (112 d.)	< 0.0001	0.013	0.729	0.006	0.001	0.420	0.623	0.677	0.008
	9 <sup>th</sup> (126 d.)	0.001	0.948	0.837	0.024	< 0.0001	0.489	0.635	0.610	0.005

<sup>\*</sup>Nitrogen mineralization significance over all incubation periods for each crop residue within individual soil series.

Table A4. Analysis of variance P-value for NH<sub>4</sub>-N mineralization for fixed effect of Crop Residue Treatment, Incubation Period, Soil Texture, and their interactions.

Source	P-value
Crop Residue Treatment	< 0.0001
Incubation Period	< 0.0001
Soil Texture	< 0.0001
Crop Residue Treatment*Incubation Period	< 0.0001
Crop Residue Treatment*Soil Texture	< 0.0001
Soil Texture*Incubation Period	< 0.0001
Crop Residue Treatment*Soil Texture*Incubation Period	< 0.0001

Table A5. Analysis of variance P-value for NO<sub>3</sub>-N mineralization for fixed effect of Crop Residue Treatment, Incubation Period, Soil Texture, and their interactions.

Source	P-value
Crop Residue Treatment	< 0.0001
Incubation Period	< 0.0001
Soil Texture	< 0.0001
Crop Residue Treatment*Incubation Period	< 0.0001
Crop Residue Treatment*Soil Texture	< 0.0001
Soil Texture*Incubation Period	0.007
Crop Residue Treatment*Soil Texture*Incubation Period	0.001

Table A6. Analysis of variance P-value for NH<sub>4</sub>-N mineralization for fixed effect Soil Texture for the Heimdal-Emrick, Fargo, and Forman soil series.

Source	P-value
Heimdal-Emrick	< 0.0001
Fargo	< 0.0001
Forman	0.107

Table A7. Analysis of variance P-value for NO<sub>3</sub>-N mineralization for fixed effect of Soil Texture for the Heimdal-Emrick, Fargo, and Forman soil series.

Source	P-value
Heimdal-Emrick	0.008
Fargo	< 0.0001
Forman	< 0.0001

Table A8. Mean and cumulative soil NH<sub>4</sub>-N mineralization over six incubation periods and five cycles with overall mean for corn, flax, pea, forage radish, soybean, spring wheat, and winter wheat crop residues and cycle means with significant differences for the Foreman soil series in North Dakota.

					Ammon	ium mineralizati	on, mg NH <sub>4</sub> kg <sup>-1</sup>	soil		
Cycle	Crop Residue	1 <sup>st</sup>	$2^{nd}$	$3^{\rm rd}$	$4^{\text{th}}$	$5^{\mathrm{th}}$	$6^{\mathrm{th}}$	Cumulative	Overall Mean§	Cycle Mean ‡
	Treatment	(14 d.)	(28 d.)	(42 d.)	(56 d.)	(70 d.)	(84 d.)			•
1 <sup>st</sup>	Soil only	0.517b†	0.703b	0.063b	0.000b	0.000a	0.000a	1.283b	$0.22b \pm 0.42$	2.77cb
	Corn	0.877b	0.310b	0.187b	0.000b	0.000a	0.013a	1.387b	$0.25b \pm 0.34$	
	Pea	2.283b	5.513b	1.287b	0.180b	0.002a	0.002a	9.267b	$1.51b \pm 2.27$	
	Radish	9.157a	47.55a	33.89a	7.393a	0.004a	0.031a	98.03a	$15.4a \pm 22.3$	
	Soybean	1.240b	0.273b	0.580b	0.007b	0.001a	0.009a	2.110b	$0.37b \pm 0.52$	
	Spring wheat	0.880b	0.950b	0.593b	0.001b	0.001a	0.004a	2.429b	$0.41b \pm 0.61$	
	Winter wheat	0.807b	0.337b	0.633b	0.000b	0.000a	0.004a	1.781b	$0.35b \pm 0.41$	
$2^{nd}$	Soil only	0.000b	0.000a	0.050a	0.013a	0.000a	0.010a	0.073a	$0.01a \pm 0.03$	1.46cd
	Corn	0.000b	0.005a	0.002a	0.140a	0.000a	0.002a	0.149a	$0.02a \pm 0.09$	
	Pea	0.960b	3.663a	0.347a	0.600a	0.000a	0.177a	5.747a	$0.93a \pm 2.22$	
	Radish	52.27a	0.006a	0.047a	0.173a	0.000a	0.001a	52.50a	$9.86a \pm 25.4$	
	Soybean	0.000b	0.001a	0.363a	0.367a	0.247a	0.210a	1.188a	$0.19a \pm 0.31$	
	Spring wheat	0.000b	0.000a	0.343a	0.423a	0.250a	0.043a	1.059a	$0.17a \pm 0.24$	
	Winter wheat	0.003b	0.001a	0.167a	0.370a	0.127a	0.063a	0.731a	$0.12a\pm0.16$	
$3^{\rm rd}$	Soil only	0.000b	0.250a	0.250a	$N/A^{\pm}$	0.817a	0.007a	1.324a	$0.15a \pm 0.33$	0.66d
	Corn	0.000b	0.647a	0.647a	N/A	0.490a	0.006a	1.790a	$0.19a \pm 0.69$	
	Pea	0.000b	3.363a	3.363a	N/A	1.893a	0.180a	8.799a	$0.96a \pm 2.14$	
	Radish	5.317a	3.480a	3.480a	N/A	1.197a	0.083a	13.56a	$2.45a \pm 4.76$	
	Sovbean	0.001b	0.001a	0.001a	N/A	0.001a	0.003a	0.007a	$0.01a \pm 0.00$	
	Spring wheat	0.002b	0.753a	0.753a	N/A	0.757a	0.030a	2.295a	$0.25a \pm 0.58$	
	Winter wheat	0.010b	0.001a	0.001a	N/A	0.000a	0.003a	0.015a	$0.02a\pm0.00$	
$4^{th}$	Soil only	3.783bc	3.767a	5.527a	3.497a	6.637a	3.367a	26.578a	$4.41a \pm 3.53$	3.56b
	Corn	3.053bc	0.253a	2.433a	1.283a	2.323a	1.530a	10.875a	$1.82a \pm 1.36$	
	Pea	12.98a	4.863a	4.610a	2.617a	5.333a	4.310a	34.713a	$5.88a \pm 3.84$	
	Radish	9.477ab	1.007a	2.177a	6.517a	5.830a	2.627a	27.635a	$4.64a \pm 4.59$	
	Soybean	1.497c	1.963a	3.363a	2.853a	4.673a	3.330a	17.679a	$2.93a \pm 1.56$	
	Spring wheat	2.167bc	1.610a	3.063a	1.890a	3.043a	4.037a	15.810a	$2.65a \pm 0.97$	
	Winter wheat	2.757bc	1.193a	3.447a	1.860a	3.840a	3.167a	16.264a	$2.72a\pm1.19$	
5 <sup>th</sup>	Soil only	3.400a	5.307a	3.700a	2.373a	5.467a	44.05a	64.297a	$11.7a \pm 15.6$	8.97a
	Corn	2.200a	2.417a	3.393a	2.227a	2.120a	21.18b	33.537a	$6.06a \pm 7.63$	
	Pea	3.697a	3.087a	5.280a	4.603a	3.160a	39.62ab	59.447a	$10.8a \pm 15.0$	
	Radish	15.75a	7.377a	3.400a	3.013a	2.800a	48.00a	80.340a	$14.8a \pm 19.3$	
	Soybean	4.483a	3.530a	4.087a	3.353a	3.957a	21.397b	40.807a	$7.28a \pm 7.27$	
	Spring wheat	4.513a	2.843a	3.333a	4.593a	3.253a	25.81b	44.345a	$7.99a \pm 10.0$	
	Winter wheat	3.073a	2.953a	3.263a	2.963a	3.013a	27.24b	42.505a	$7.71a \pm 10.4$	

<sup>†</sup>Different letters within a column for each incubation cycle are significantly different at the 0.05 level using Tukey's HSD test.

<sup>&</sup>lt;sup>±</sup> Incubation malfunction resulting in no data

<sup>§</sup> Nitrogen mineralization mean over all incubation periods for each crop residue treatment.

<sup>&</sup>lt;sup>‡</sup> Nitrogen mineralization mean over all incubation periods including all crop residue treatments.

Table A9. Analysis of variance P-value for NH<sub>4</sub>-N mineralization for fixed effect of Crop Residue Treatment, Incubation Period, Freeze and Thaw Cycle, and their interactions.

Source	P-value
Crop Residue Treatment	< 0.0001
Freeze and Thaw Cycle	< 0.0001
Incubation Period	< 0.0001
Crop Residue Treatment*Freeze and Thaw Cycle	< 0.0001
Crop Residue Treatment*Incubation Period	< 0.0001
Freeze and Thaw Cycle*Incubation Period	< 0.0001
Crop Residue Treatment*Freeze and Thaw Cycle*Incubation Period	< 0.0001

Table A10. Analysis of variance P-value for NO<sub>3</sub>-N mineralization for fixed effect of Crop Residue Treatment, Incubation Period, Freeze and Thaw Cycle, and their interactions.

Source	P-value
Crop Residue Treatment	< 0.0001
Freeze and Thaw Cycle	< 0.0001
Incubation Period	< 0.0001
Crop Residue Treatment*Freeze and Thaw Cycle	< 0.0001
Crop Residue Treatment*Incubation Period	< 0.0001
Freeze and Thaw Cycle*Incubation Period	< 0.0001
Crop Residue Treatment*Freeze and Thaw Cycle*Incubation Period	< 0.0001

Table A11. Analysis of variance P-value for NH<sub>4</sub>-N mineralization for fixed effect of Freeze and Thaw Cycles.

Source	P-value
Cycle 1	< 0.0001
Cycle 2	0.0027
Cycle 3	0.1694
Cycle 4	< 0.0001
Cycle 5	< 0.0001

Table A12. Analysis of variance P-value for NO<sub>3</sub>-N mineralization for fixed effect of Freeze and Thaw Cycles.

Source	P-value
Cycle 1	0.0011
Cycle 2	< 0.0001
Cycle 3	< 0.0001
Cycle 4	< 0.0001
Cycle 5	< 0.0001

Table A13. Analysis of variance P-value for NO<sub>3</sub>-N mineralization split by fixed effect of Freeze and Thaw Cycles and Incubation Periods.

110020 0110	Thaw Cycles and II		<u></u>	P-v	alue		
Cycle	Crop Residue	1 <sup>st</sup>	$2^{\text{nd}}$	3 <sup>rd</sup>	4 <sup>th</sup>	5 <sup>th</sup>	6 <sup>th</sup>
	Treatment	(14 d.)	(28 d.)	(42 d.)	(56 d.)	(70 d.)	(84 d.)
1 <sup>st</sup>	Soil only	0.1801	0.8309	0.8580	0.4339	0.7402	0.3147
	Corn	0.0210	0.9645	1.0000	0.9842	1.0000	0.9943
	Pea	0.1267	0.7965	0.7802	0.4463	0.7449	0.2845
	Radish	< 0.0001	0.0009	0.0002	< 0.0001	< 0.0001	< 0.0001
	Soybean	0.1252	0.9657	1.0000	0.9518	0.9742	0.9487
	Spring wheat	0.0396	0.9645	1.0000	0.9784	0.9881	0.9726
	Winter wheat	0.1278	1.0000	1.0000	0.9806	1.0000	0.9806
2 <sup>nd</sup>	Soil only	0.7317	0.0461	0.4090	0.6682	0.2868	0.0541
	Corn	1.0000	0.9230	1.0000	1.0000	1.0000	0.9988
	Pea	0,8959	< 0.0001	0.0390	0.0817	0.0006	< 0.0001
	Radish	0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
	Soybean	1.0000	1.0000	0.9827	1.0000	0.9779	0.9458
	Spring wheat	1.0000	1.0000	0.9975	1.0000	1.0000	0.9823
	Winter wheat	1.0000	0.9851	1.0000	1.0000	1.0000	0.9941
3 <sup>rd</sup>	Soil only	0.7587	0.6001	0.6010	0.3902	0.1765	0.2861
	Corn	1.0000	1.0000	0.9999	1.0000	1.0000	0.9964
	Pea	0.0196	0.0058	0.0058	0.0014	< 0.0001	< 0.0001
	Radish	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
	Soybean	1.0000	1.0000	1.0000	0.9936	1.0000	0.9964
	Spring wheat	0.9937	1.0000	1.0000	0.9993	1.0000	0.9946
	Winter wheat	1.0000	1.0000	1.0000	0.9993	1.0000	0.9692
4 <sup>th</sup>	Soil only	< 0.0001	0.1053	0.0084	0.0613	0.0002	0.0009
	Corn	0.8665	0,9729	0.6323	0.8793	0.9413	0.9511
	Pea	0.0018	0.0708	0.0209	0.0016	< 0.0001	< 0.0001
	Radish	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
	Soybean	1.0000	0.9281	0.8480	0.9215	0.8942	0.8315
	Spring wheat	0.7014	0.9957	0.9402	0.8249	0.9274	0.9667
	Winter wheat	1.0000	0.9441	0.8927	0.8001	0.9246	0.9004
5 <sup>th</sup>	Soil only	< 0.0001	0.0223	0.0518	0.0052	0.0002	1.0000
	Corn	0.8675	0.9435	0.5841	0.5339	0.5463	1.0000
	Pea	< 0.0001	0.0003	0.0019	< 0.0001	< 0.0001	1.0000
	Radish	< 0.0001	0.0023	< 0.0001	< 0.0001	< 0.0001	0.0007
	Soybean	1.0000	0.9008	0.6542	0.7382	0.9704	1.0000
	Spring wheat	0.8703	0.9474	0.7370	0.5171	0.7833	1.0000
	Winter wheat	1.0000	0.9353	0.6459	0.5253	0.6713	1.0000

Table A14. Analysis of variance P-value for NH<sub>4</sub>-N mineralization split by fixed effect of Freeze and Thaw Cycles and Incubation Periods.

				P-v	alue		
Cycle	Crop Residue	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	5 <sup>th</sup>	6 <sup>th</sup>
•	Treatment	(14 d.)	(28 d.)	(42 d.)	(56 d.)	(70 d.)	(84 d.)
1 <sup>st</sup>	Soil only	0.2800	0.8519	0.9923	1.0000	1.0000	1.0000
	Corn	0.0773	0.9344	0.9772	1.0000	1.0000	0.0192
	Pea	0.0002	0.1582	0.8437	0.9467	1.0000	1.0000
	Radish	< 0.0001	< 0.0001	0.0001	0.0143	1.0000	1.0000
	Soybean	0.0174	0.9421	0.9292	0.9980	1.0000	1.0000
	Spring wheat	0.0763	0.8010	0.9275	1.0000	0.5314	1.0000
	Winter wheat	0.1012	0.9288	0.9227	0.9132	0.0224	1.0000
$2^{\text{nd}}$	Soil only	1.0000	1.0000	0.7498	0.9533	1.0000	0.9055
	Corn	1.0000	1.0000	1.0000	0.5417	1.0000	1.0000
	Pea	0.9243	0.0043	0.0406	0.0179	1.0000	0.0509
	Radish	0.0001	1.0000	0.7659	0.4516	1.0000	1.0000
	Soybean	1.0000	1.0000	0.0331	0.1237	0.0119	0.0236
	Spring wheat	1.0000	1.0000	0.0423	0.0795	0.0110	0.6086
	Winter wheat	1.0000	1.0000	0.2966	0.1206	0.1601	0.4566
$3^{\text{rd}}$	Soil only	1.0000	0.8672	0.8672	N/A <sup>†</sup>	0.1452	1.0000
	Corn	1.0000	0.6662	0.6660	N/A	0.3704	1.0000
	Pea	1.0000	0.0379	0.0037	N/A	0.0030	0.0324
	Radish	0.0192	0.0326	0.0326	N/A	0.0403	0.2903
	Soybean	1.0000	1.0000	1.0000	N/A	1.0000	1.0000
	Spring wheat	1.0000	0.6157	0.6150	N/A	0.1749	0.6983
	Winter wheat	1.0000	1.0000	1.0000	N/A	1.0000	1.0000
4 <sup>th</sup>	Soil only	0.0325	0.0023	0.0002	0.0449	0.0031	0.0032
	Corn	0.0761	0.8063	0.0501	0.4324	0.2317	0.1287
	Pea	< 0.0001	0.0003	0.0012	0.1215	0.0124	0.0005
	Radish	< 0.0001	0.3375	0.0757	0.0011	0.0073	0.0150
	Soybean	0.3637	0.0732	0.0103	0.0939	0.0248	0.0034
	Spring wheat	0.1956	0.1345	0.0173	0.2536	0.1238	0.0008
	Winter wheat	0.1057	0.2587	0.0089	0.2609	0.0578	0.0048
5 <sup>th</sup>	Soil only	0.4697	0.0097	0.0147	0.1557	0.0001	< 0.0001
	Corn	0.6381	0.1944	0.0231	0.1810	0.0643	0.0120
	Pea	0.4327	0.1036	0.0014	0.0114	0.0097	< 0.0001
	Radish	0.0040	0.0010	0.0228	0.0775	0.0189	< 0.0001
	Soybean	0.3438	0.0664	0.0083	0.0524	0.0022	0.0113
	Spring wheat	0.3407	0.1311	0.0252	0.0115	0.0081	0.0034
	Winter wheat	0.5127	0.1180	0.0278	0.0820	0.0127	0.0023

<sup>†</sup> Incubation malfunction resulting in no data

Table A15. Analysis of variance P-value for NO<sub>3</sub>-N and NH<sub>4</sub>-N mineralization split by fixed effect of Crop Residue Treatment.

		P-value			
Cycle	Crop Residue Treatment	NO <sub>3</sub> -N Overall	NH <sub>4</sub> -N Overall		
1 <sup>st</sup>	Soil only	0.2871	0.9270		
	Corn	0.7430	0.9168		
	Pea	0.2498	0.5247		
	Radish	< 0.0001	< 0.0001		
	Soybean	0.7888	0.8757		
	Spring wheat	0.7585	0.8635		
	Winter wheat	0.8321	0.8815		
nd	Soil only	0.4723	0.9965		
	Corn	0.9943	0.9935		
	Pea	0.0326	0.7302		
	Radish	< 0.0001	0.0045		
	Soybean	0.9895	0.9433		
	Spring wheat	0.9981	0.9507		
	Winter wheat	0.9984	0.9659		
3 <sup>rd</sup>	Soil only	0.7253	0.8870		
	Corn	0.9996	0.8560		
	Pea	0.0285	0.3648		
	Radish	< 0.0001	0.0312		
	Soybean	0.9994	1.0000		
	Spring wheat	0.9971	0.8094		
	Winter wheat	0.9962	1.0000		
4 <sup>th</sup>	Soil only	0.0079	0.0006		
	Corn	0.8940	0.0904		
	Pea	0.0009	< 0.0001		
	Radish	< 0.0001	0.0004		
	Soybean	0.9244	0.0111		
	Spring wheat	0.9300	0.0194		
	Winter wheat	0.9068	0.0169		
5 <sup>th</sup>	Soil only	0.0197	0.0068		
	Corn	0.7876	0.1146		
	Pea	0.0003	0.0107		
	Radish	< 0.0001	0.0015		
	Soybean	0.8617	0.0641		
	Spring wheat	0.8304	0.0450		
	Winter wheat	0.8247	0.0518		

Table A16. Mean and cumulative NH<sub>4</sub>-N mineralization over three incubations with five leaching periods and two freeze and thaw cycles for corn (C), radish (R), soybean (S), and spring wheat (SW) crop residues for the Forman soil series in North Dakota.

Mean nitrogen mineralization per leaching period (days), mg NH<sub>4</sub> kg<sup>-1</sup> Incubation Crop Residue Treatment 1st (14 d.) 2<sup>nd</sup> (28 d.) 3rd (42 d.) 4th (56 d.) 5<sup>th</sup> (70 d.) Cumulative Overall Mean§ Incubation Mean ¶ 0.083a‡ 0.199a 1.241a -0.527a -0.969a  $-0.19a \pm 2.46$ -0.312a Soil only† -1.965a <u>C</u>-C-C -1.626a -1.369a -2.001a 0.428a -1.712a -6.28a  $-1.22a \pm 2.72$ C-S-C -0.770a -0.856a 0.481a 2.396a 0.428a 1.679a  $0.39a \pm 3.75$ <u>S</u>-C-S -0.008a 2.054a -1.060a 0.770a -2.482a -0.726a  $-0.03a \pm 2.91$ -2.225a SW-S-SW -1.113a 1.284a -1.915a 1.113a -2.856a  $-0.46a \pm 2.50$ S-SW-S -0.770a 1.027a -1.915a 1.198a -1.369a -1.829a  $-0.30a \pm 3.24$ SW-S-C 3.509a -1.027a -1.659a 0.685a -2.567a -1.059a  $-0.06a \pm 3.41$ S-C-SW -1.540a 4.878a -1.915a 0.428a -2.995a -1.144a  $-0.03a \pm 3.64$ C-SW-S -1.198a 2.054a -2.172a 0.513a -1.626a -2.429a  $-0.40a \pm 2.61$ SW/R-S/R-C -1.626a 1.113a -2.172a 0.428a -3.509a -5.766a  $-1.03a \pm 3.35$ S/R-C-SW/R -0.770a -0.599a 0.685a -2.139a -3.968a -1.145a  $-0.73a \pm 3.00$  $\underline{C}$ -SW/R-S/R -1.712a 1.626a -2.172a 1.626a -2.567a -3.199a  $-0.49a \pm 3.18$ R-R-R 3.081a 6.846a -0.290a 2.225a -3.508a 8.354a  $1.85a \pm 7.43$  $2^{nd}$ Soil only 1.883a 0.157a 0.464a -0.201a 1.098a 3.401a  $0.50a \pm 1.87$ -0.359a C-<u>C</u>-C 0.385a -1.25ab -0.342a 0.342a -1.669a -2.534ab  $-0.4ab \pm 1.02$ 1.925a -2.267a -3.502ab C-S-C -1.62ab -1.027a -0.513a  $-0.6ab \pm 1.48$ S-C-S -1.49ab -0.342a -2.182a -4.056ab  $-0.8ab \pm 1.27$ 1.284a -1.326a SW-S-SW 0.984a -2.31b -1.669a -0.342a -2.353a -5.69b  $-1.10b \pm 1.36$ S-SW-S 0.428a 2.439a -0.77ab 0.086a -1.241a 0.942ab  $0.10ab \pm 1.65$ SW-S-C 2.311a -1.19ab 0.299a -0.342a -2.353a -1.275ab  $-0.4ab \pm 1.63$  $-0.2ab \pm 1.54$ S-C-SW 1.840a -1.41ab 0.342a -0.214a -1.669a -1.111ab C-SW-S 2.696a -1.67ab 0.342a -0.085a -2.182a -0.899ab  $-0.2ab \pm 1.87$ SW/R-S/R-C 1.583a -1.49ab -0.984a -0.642a -2.396a -3.929ab  $-0.8ab \pm 1.32$ S/R-C-SW/R 1.626a -1.24ab -0.556a 0.001a -1.840a -2.009ab  $-0.4ab \pm 1.26$ C-SW/R-S/R -1.58ab -0.941a -2.567a -3.419ab  $-0.8ab \pm 1.77$ 2.482a -0.813a R-R-R 2.567a 0.599a -0.257a -0.342a -1.669a 0.898ab  $0.02ab \pm 1.55$  $3^{rd}$ Soil only -0.307a 0.278a 0.093a 0.107a 0.488a 0.659ab  $0.08ab \pm 0.66$ -0.028a C-C-C -0.086a 0.299a -0.299a -0.171a -0.513a -0.77ab  $0.04ab \pm 0.84$ C-S-C -0.086a -0.599a -0.171a -0.428a -0.685a -1.969ab  $-0.1ab \pm 0.92$ S-C-S 0.342a -0.642a 0.001a -0.086a -0.257a -0.642ab  $-0.0ab \pm 0.94$ SW-S-SW -0.342a -0.556a -0.513a -0.770a -0.471a -2.652b  $-0.23b \pm 0.90$  $0.51ab \pm 1.02$ S-SW-S -0.128a 0.214a -0.086a -0.128a 1.027ab 1.155a SW-S-C 0.599a -0.257a 0.342a 0.428a -0.086a 1.026ab  $0.35ab \pm 0.76$ S-C-SW 0.128a 0.001a 0.171a -0.342a -0.257a -0.299ab  $0.34ab \pm 0.89$ C-SW-S -0.043a 0.299a -0.001a -0.513a -0.001a -0.259ab  $0.21ab \pm 0.72$ SW/R-S/R-C -0.599a -0.556a -0.428a -0.685a -0.599a -2.867b  $-0.46b \pm 0.55$ S/R-C-SW/R -0.385a 0.257a 0.556a 0.770a 0.171a 1.369ab  $0.55ab \pm 1.10$ C-SW/R-S/R -0.471a 0.086a -0.989ab -0.685a -0.004a 0.085a  $0.00ab \pm 0.80$ R-R-R 2.139a 0.513a 1.198a -0.086a 0.813a 4.577a  $1.41a \pm 1.57$ 

<sup>†</sup>Underlined crop residue(s) indicate the current crops(s) represented in the incubation cycle

Different letters within a column are significantly different for each incubation cycle at the 0.05 level using Tukey's HSD test.

<sup>§</sup> Nitrogen mineralization mean over all incubation periods for each crop residue treatment.

Nitrogen mineralization mean over all incubation periods including all crop residue treatments.

Table A17. Analysis of variance P-value for NH<sub>4</sub>-N mineralization for fixed effect of crop residue treatment, leaching period, incubation series, and their interactions.

Source	P-value
Crop Residue Treatment	0.0029
Incubation Series	0.0262
Leaching Period	< 0.0001
Crop Residue Treatment*Incubation Series	0.8830
Crop Residue Treatment*Leaching Period	0.9996
Incubation Series*Leaching Period	< 0.0001
Crop Residue Treatment*Incubation Series*Leaching Period	1.000

Table A18. Analysis of variance P-value for NO<sub>3</sub>-N mineralization for fixed effect of crop residue treatment, leaching period, incubation series, and their interactions.

Source	P-value
Crop Residue Treatment	< 0.0001
Incubation Series	< 0.0001
Leaching Period	0.1485
Crop Residue Treatment*Incubation Series	0.1666
Crop Residue Treatment*Leaching Period	< 0.0001
Incubation Series*Leaching Period	< 0.0001
Crop Residue Treatment*Incubation Series*Leaching Period	0.0001

Table A19. Analysis of variance P-value for NH<sub>4</sub>-N mineralization for fixed effect of incubation series.

Source	P-value
Incubation 1	0.3883
Incubation 2	0.0439
Incubation 3	0.0417

Table A20. Analysis of variance P-value for NO<sub>3</sub>-N mineralization for fixed effect of incubation series.

Source	P-value
Incubation 1	< 0.0001
Incubation 2	< 0.0001
Incubation 3	< 0.0001

Table A21. Analysis of variance P-value for NO<sub>3</sub>-N and NH<sub>4</sub>-N mineralization split by

fixed effect of crop residue treatment.

	of crop residue treatment.		P-value		
Incubation	Crop Residue Treatment	NO <sub>3</sub> -N Overall	NH <sub>4</sub> -N Overall		
1 <sup>st</sup>	Soil only <sup>†</sup>	0.4480	0.7932		
	<u>C</u> -C-C	0.0761	0.0985		
	<u>C</u> -S-C	0.1336	0.5973		
	$\overline{S}$ -C-S	0.0448	0.9600		
	SW-S-SW	0.1042	0.5243		
	$\overline{S}$ -SW-S	0.0063	0.6832		
	SW-S-C	0.0320	0.9372		
	<u>S</u> -C-SW	0.0343	0.9668		
	C-SW-S	0.0505	0.5875		
	$\overline{SW/R}$ -S/R-C	0.8687	0.1604		
	$\overline{S/R}$ -C-SW/R	0.2338	0.3184		
	$\overline{\text{C-S}}\text{W/R-S/R}$	0.1065	0.4986		
	<u>R</u> -R-R	< 0.0001	0.0129		
2 <sup>nd</sup>	Soil only	0.1761	0.1110		
	C- <u>C</u> -C	0.0028	0.2150		
	C- <u>S</u> -C	0.0008	0.0526		
	S-C-S	0.0016	0.0202		
	<u></u> SW- <u>S</u> -SW	0.0002	0.0010		
	S- <u>SW</u> -S	0.0084	0.7451		
	SW- <u>S</u> -C	0.0007	0.2432		
	S- <u>C</u> -SW	0.0014	0.4836		
	$C-\overline{SW}-S$	0.0008	0.4081		
	SW/R-S/R-C	0.0057	0.0092		
	S/R-C-SW/R	0.0007	0.1748		
	C- <u>SW/R</u> -S/R	0.0029	0.0126		
	R- <u>R</u> -R	< 0.0001	0.9305		
5 <sup>th</sup>	Soil only	0.6903	0.7845		
	C-C-C	0.3544	0.8811		
	C-S- <u>C</u>	0.5303	0.6619		
	S-C- <u>S</u>	0.8158	0.8509		
	SW-S- <u>SW</u>	0.7627	0.4662		
	S-SW- <u>S</u>	0.3414	0.1211		
	SW-S- <u>C</u>	0.6621	0.2766		
	S-C- <u>SW</u>	0.5069	0.2919		
	C-SW- <u>S</u>	0.2921	0.5283		
	SW/R-S/R- <u>C</u>	0.8651	0.1610		
	$S/R - C - \frac{SW}{R}$	0.8243	0.1009		
	C-SW/R-S/R	0.6356	0.9893		
	R-R- <u>R</u>	< 0.0001	< 0.0001		

<sup>†</sup>Underlined crop residue(s) indicate the current crops(s) represented in the incubation cycle

## A.2. Additional Figures

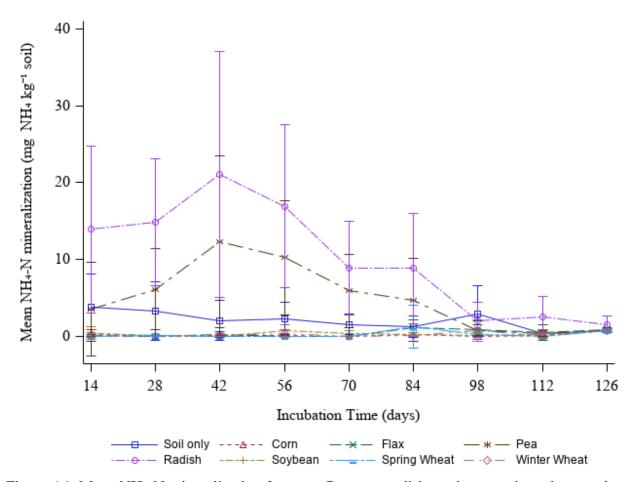


Figure A1. Mean NH<sub>4</sub>-N mineralization for corn, flax, pea, radish, soybean, spring wheat, and winter wheat crop residues over nine incubation periods, regardless of soil type.

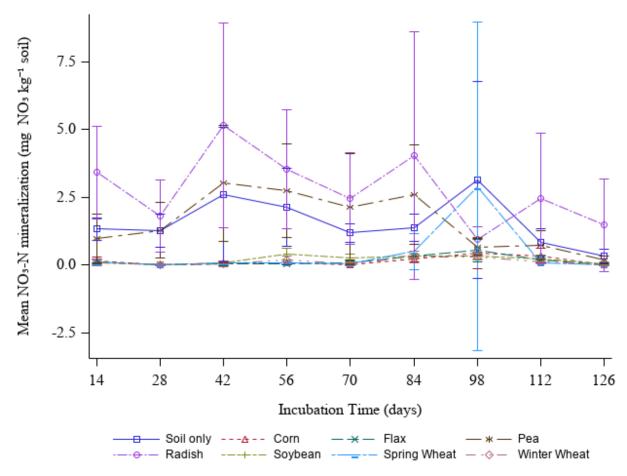


Figure A2. Mean NO<sub>3</sub>-N mineralization for the control (bare, unamended soil), corn, flax, pea, radish, soybean, spring wheat, and winter wheat crop residues over nine incubation periods, regardless of soil type.

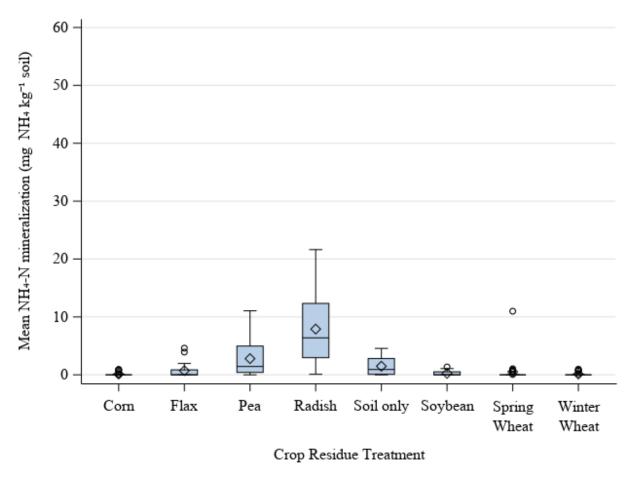


Figure A3. Mean NH<sub>4</sub>-N mineralization distribution for control (bare, unamended soil), corn, flax, pea, radish, soybean, spring wheat, and winter wheat crop residues for the Heimdal-Emrick soil series over all incubation periods.

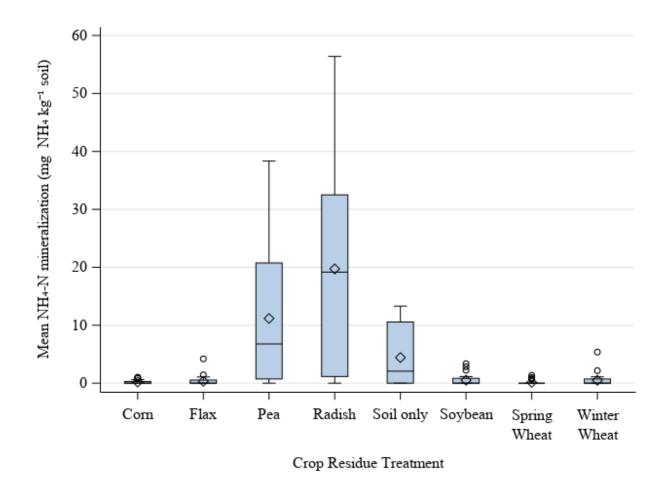


Figure A4. Mean NH<sub>4</sub>-N mineralization distribution for control (bare, unamended soil), corn, flax, pea, radish, soybean, spring wheat, and winter wheat crop residues for the Fargo soil series over all incubation periods.

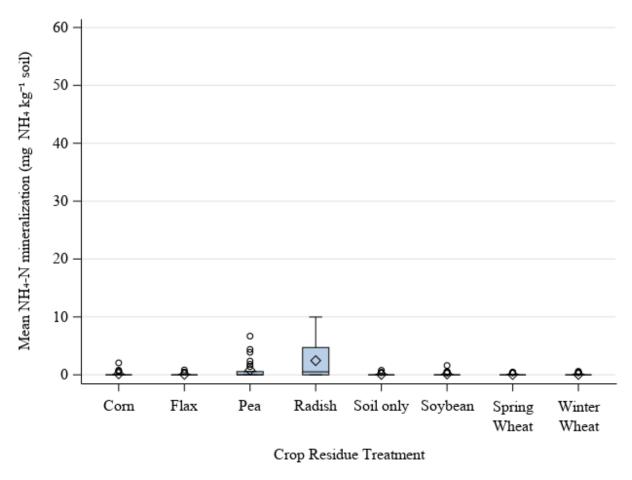


Figure A5. Mean NH<sub>4</sub>-N mineralization distribution for control (bare, unamended soil), corn, flax, pea, radish, soybean, spring wheat, and winter wheat crop residues for the Forman soil series over all incubation periods.

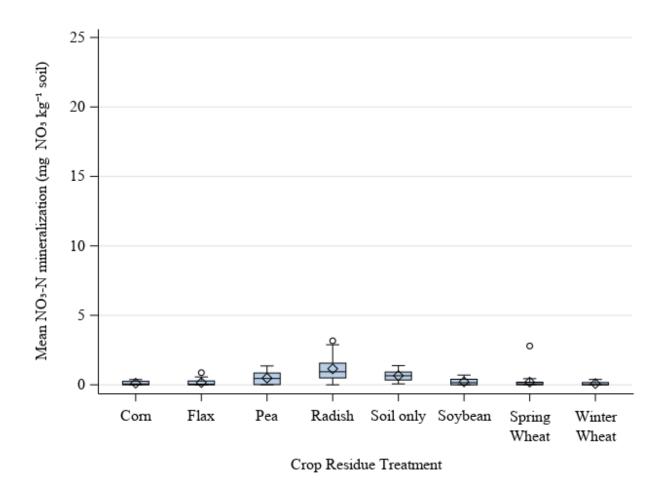


Figure A6. Mean NO<sub>3</sub>-N mineralization distribution for control (bare, unamended soil), corn, flax, pea, radish, soybean, spring wheat, and winter wheat crop residues for the Heimdal-Emrick soil series over all incubation periods.

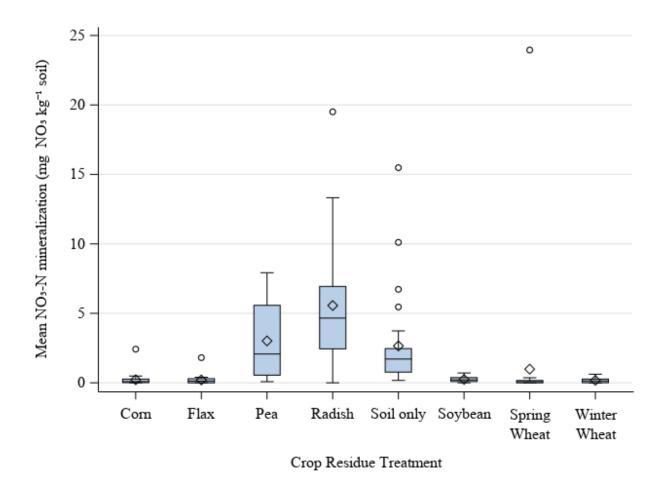


Figure A7. Mean NO<sub>3</sub>-N mineralization distribution for control (bare, unamended soil), corn, flax, pea, radish, soybean, spring wheat, and winter wheat crop residues for the Fargo soil series over all incubation periods.

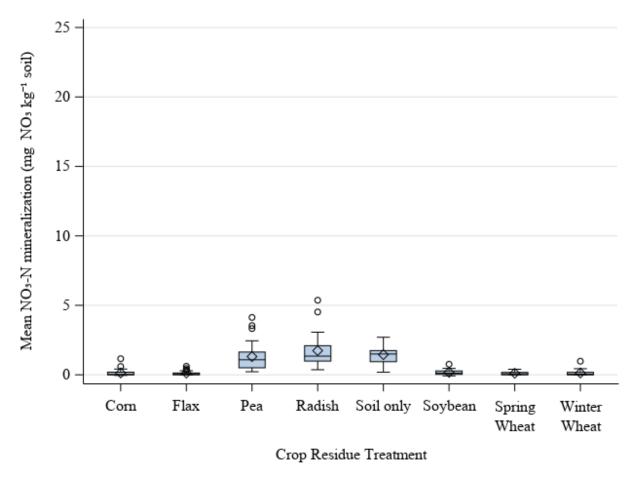


Figure A8. Mean NO<sub>3</sub>-N mineralization distribution for control (bare, unamended soil), corn, flax, pea, radish, soybean, spring wheat, and winter wheat crop residues for the Forman soil series over all incubation periods.

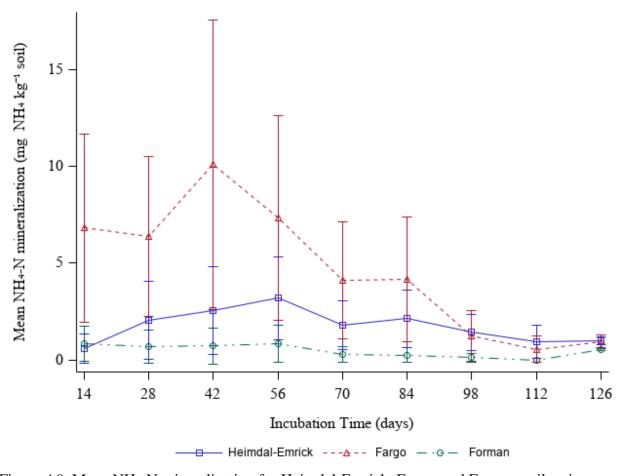


Figure A9. Mean NH<sub>4</sub>-N mineralization for Heimdal-Emrick, Fargo, and Forman soil series over nine incubation periods, regardless of crop residue treatment.

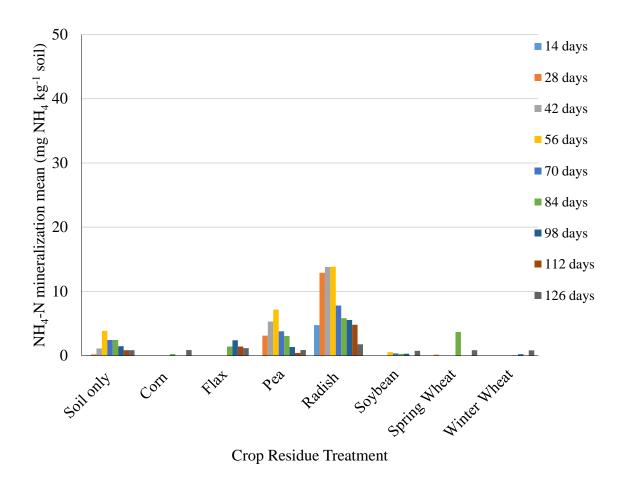


Figure A10. Mean NH<sub>4</sub>-N mineralization patterns over time for control, corn, flax, pea, radish, soybean, spring wheat, and winter where crop residue treatment for the Heimdal-Emrick soil series.

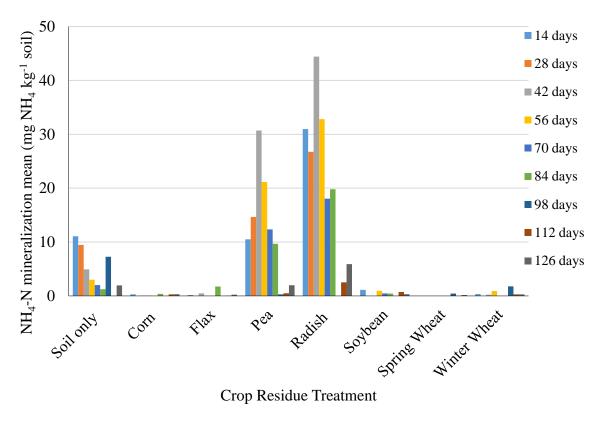


Figure A11. Mean NH<sub>4</sub>-N mineralization patterns over time for control, corn, flax, pea, radish, soybean, spring wheat, and winter where crop residue treatment for the Fargo soil series.

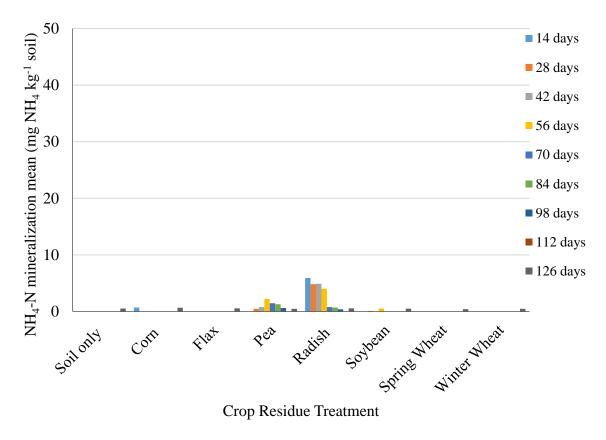


Figure A12. Mean NH<sub>4</sub>-N mineralization patterns over time for control, corn, flax, pea, radish, soybean, spring wheat, and winter where crop residue treatment for the Forman soil series.

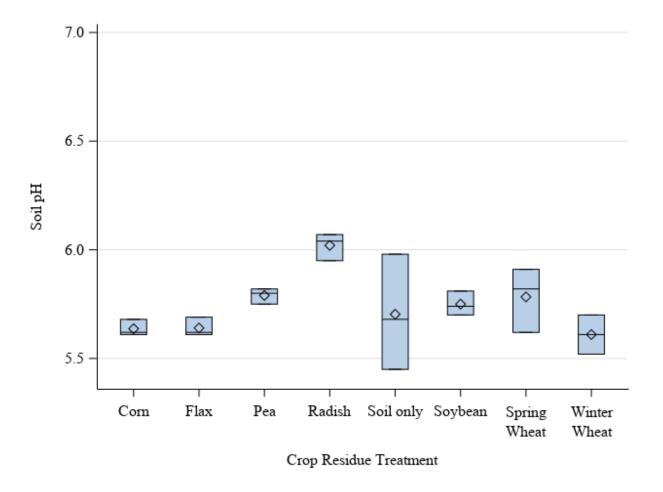


Figure A13. Soil pH distribution for control (bare, unamended soil), corn, flax, pea, radish, soybean, spring wheat, and winter wheat crop residues for the Heimdal-Emrick soil series over all incubation periods.

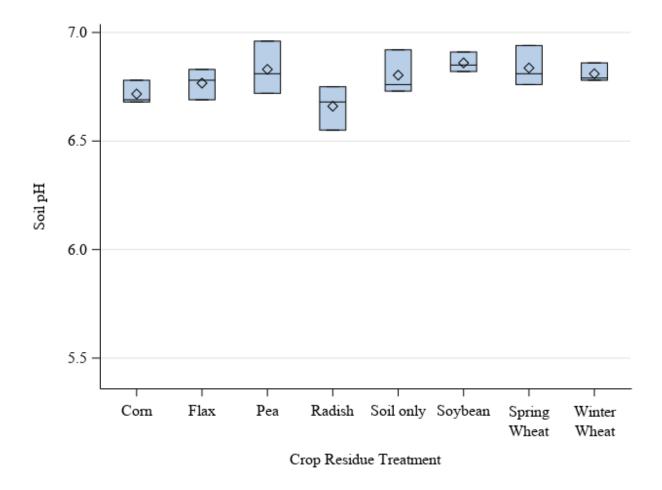


Figure A14. Soil pH distribution for control (bare, unamended soil), corn, flax, pea, radish, soybean, spring wheat, and winter wheat crop residues for the Fargo soil series over all incubation periods.

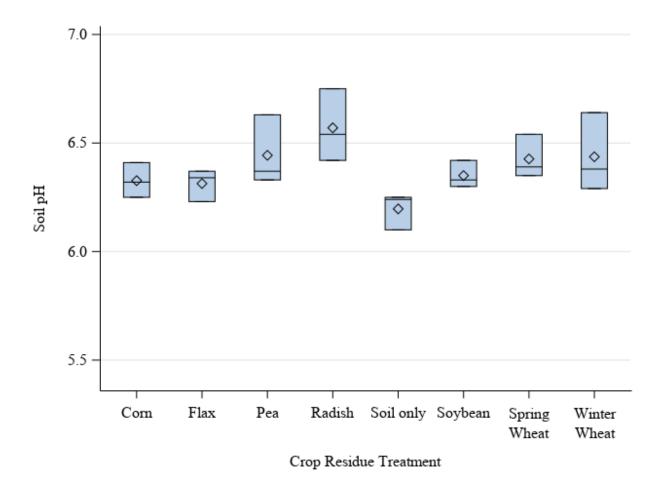


Figure A15. Soil pH distribution for control (bare, unamended soil), corn, flax, pea, radish, soybean, spring wheat, and winter wheat crop residues for the Forman soil series over all incubation periods.

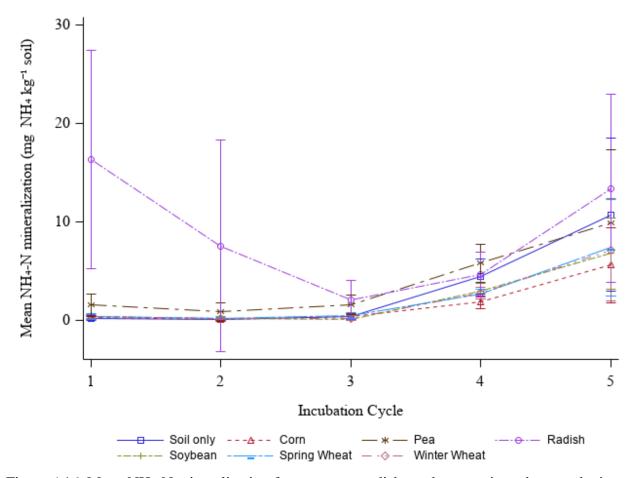


Figure A16. Mean NH<sub>4</sub>-N mineralization for corn, pea, radish, soybean, spring wheat, and winter wheat crop residues over five incubation cycles in the Foreman soil series.

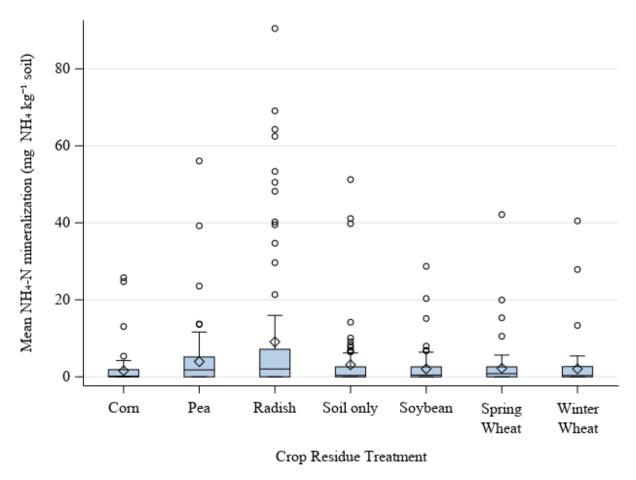


Figure A17. Mean NH<sub>4</sub>-N mineralization distribution for control (bare, unamended soil), corn, pea, radish, soybean, spring wheat, and winter wheat crop residue treatments in the Foreman soil series.

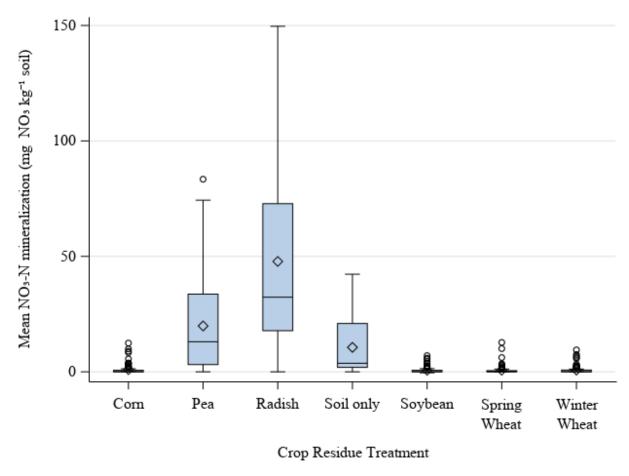


Figure A18. Mean NO<sub>3</sub>-N mineralization distribution for control (bare, unamended soil), corn, pea, radish, soybean, spring wheat, and winter wheat crop residue treatments in the Foreman soil series.

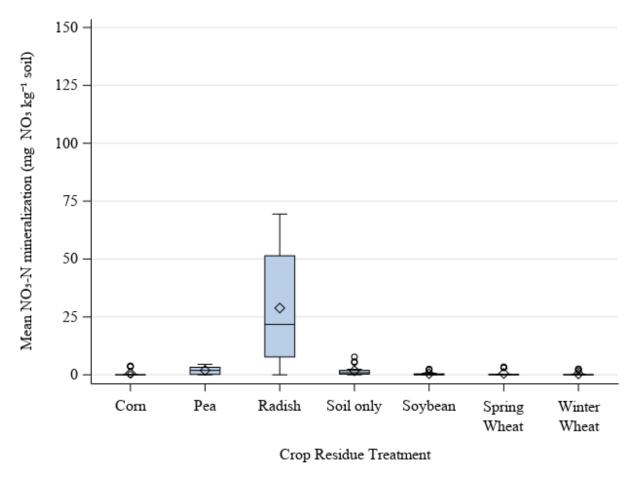


Figure A19. Mean NO<sub>3</sub>-N mineralization distribution for control (bare, unamended soil), corn, pea, radish, soybean, spring wheat, and winter wheat crop residue treatments for the first incubation cycle in the Foreman soil series.

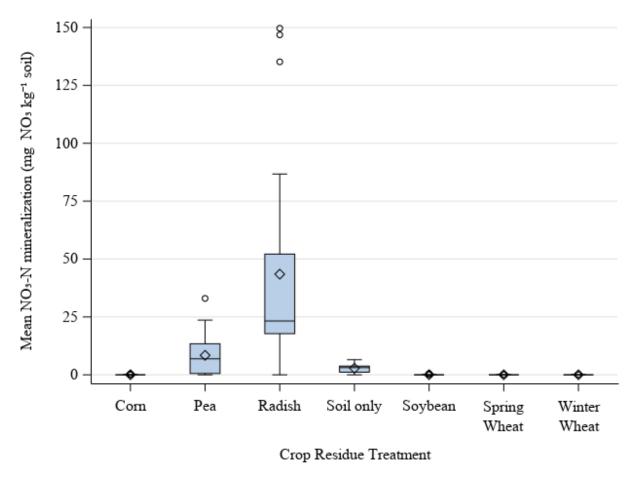


Figure A20. Mean NO<sub>3</sub>-N mineralization distribution for control (bare, unamended soil), corn, pea, radish, soybean, spring wheat, and winter wheat crop residue treatments for the second incubation cycle in the Foreman soil series.

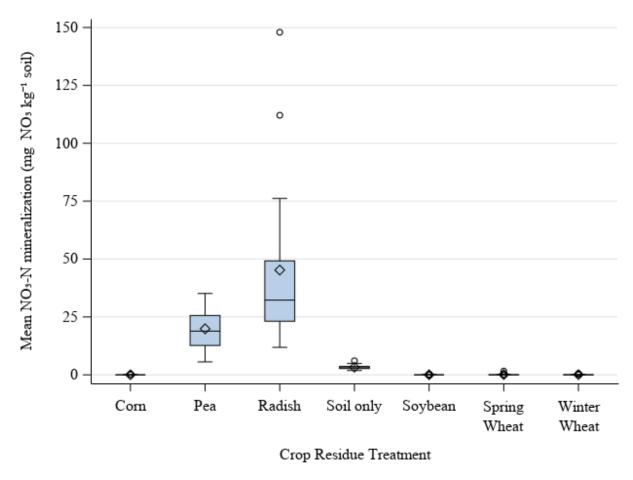


Figure A21. Mean NO<sub>3</sub>-N mineralization distribution for control (bare, unamended soil), corn, pea, radish, soybean, spring wheat, and winter wheat crop residue treatments for the third incubation cycle in the Foreman soil series.

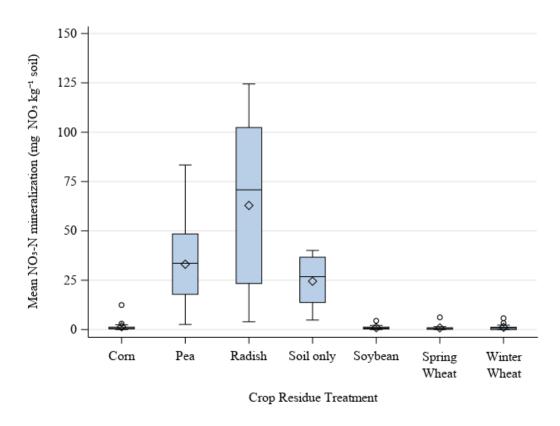


Figure A22. Mean NO<sub>3</sub>-N mineralization distribution for control (bare, unamended soil), corn, pea, radish, soybean, spring wheat, and winter wheat crop residue treatments for the fourth incubation cycle in the Foreman soil series.

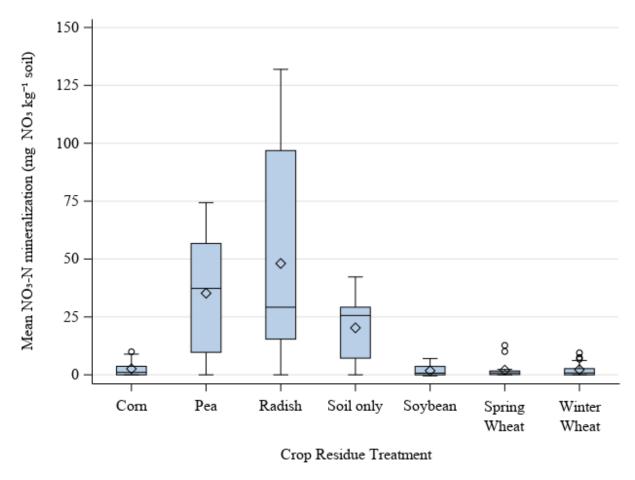


Figure A23. Mean NO<sub>3</sub>-N mineralization distribution for control (bare, unamended soil), corn, pea, radish, soybean, spring wheat, and winter wheat crop residue treatments for the fifth incubation cycle in the Foreman soil series.

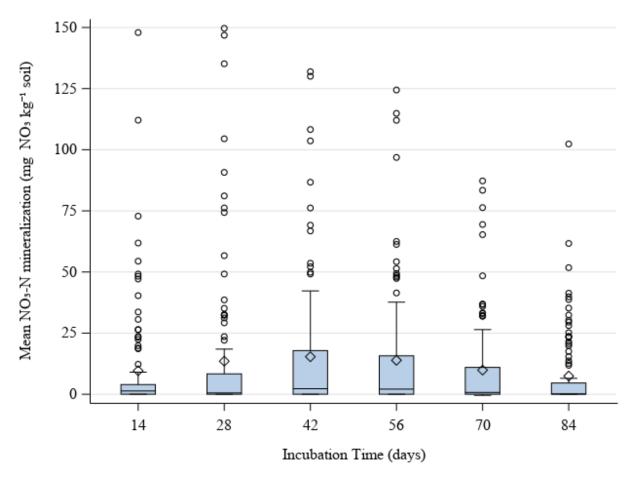


Figure A24. Mean NO<sub>3</sub>-N mineralization distribution for control (bare, unamended soil), corn, pea, radish, soybean, spring wheat, and winter wheat crop residue treatments over six incubation periods, regardless of five incubation cycles, in the Foreman soil series.

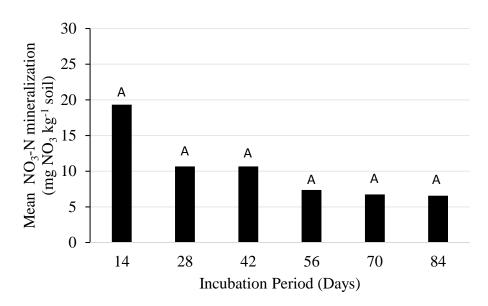


Figure A25. Mean NO<sub>3</sub>-N mineralization patterns, regardless of crop residue treatments, over six incubation periods for the first incubation cycle with significance differences in values indicated among the incubation periods.

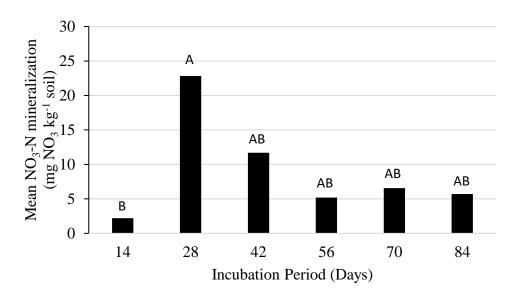


Figure A26. Mean NO<sub>3</sub>-N mineralization patterns, regardless of crop residue treatments, over six incubation periods for the second incubation cycle with significance differences in values indicated among the incubation periods.

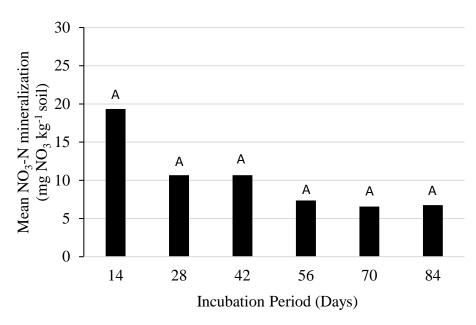


Figure A27. Mean NO<sub>3</sub>-N mineralization patterns, regardless of crop residue treatments, over six incubation periods for the third incubation cycle with significance differences in values indicated among the incubation periods.

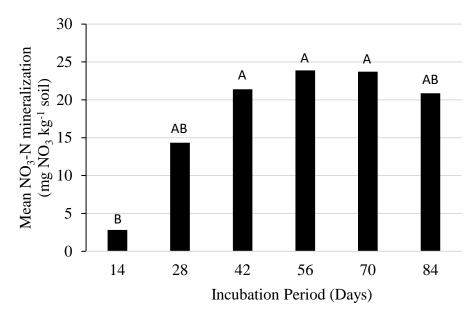


Figure A28. Mean NO<sub>3</sub>-N mineralization patterns, regardless of crop residue treatments, over six incubation periods for the fourth incubation cycle with significance differences in values indicated among the incubation periods.

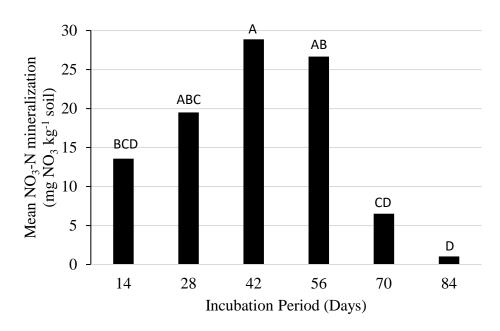


Figure A29. Mean NO<sub>3</sub>-N mineralization patterns, regardless of crop residue treatments, over six incubation periods for the fifth incubation cycle with significance differences in values indicated among the incubation periods.

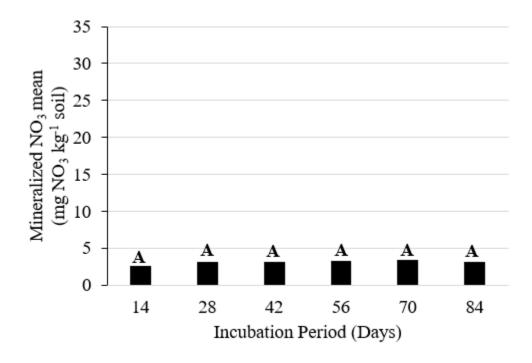


Figure A30. Mean NO<sub>3</sub>-N mineralization patterns for the bare, unamended soil over six incubation periods for the first incubation cycle with significance differences in values indicated among the incubation periods.

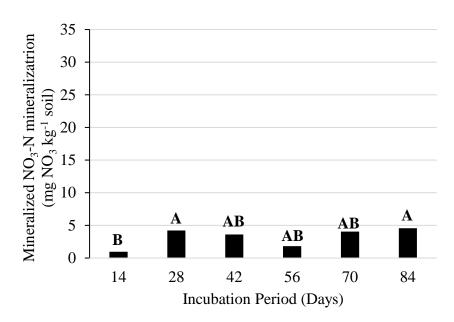


Figure A31. Mean NO<sub>3</sub>-N mineralization patterns for the bare, unamended soil over six incubation periods for the second incubation cycle with significance differences in values indicated among the incubation periods.

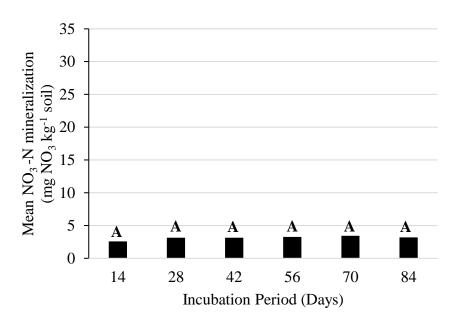


Figure A32. Mean NO<sub>3</sub>-N mineralization patterns for the bare, unamended soil over six incubation periods for the third incubation cycle with significance differences in values indicated among the incubation periods.

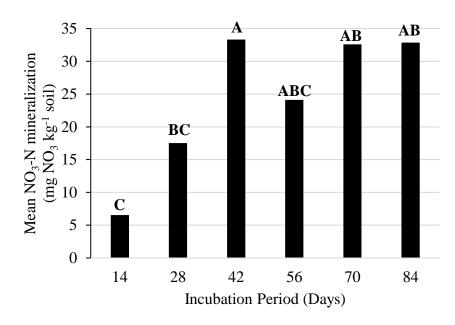


Figure A33. Mean NO<sub>3</sub>-N mineralization patterns for the bare, unamended soil over six incubation periods for the fourth incubation cycle with significance differences in values indicated among the incubation periods.

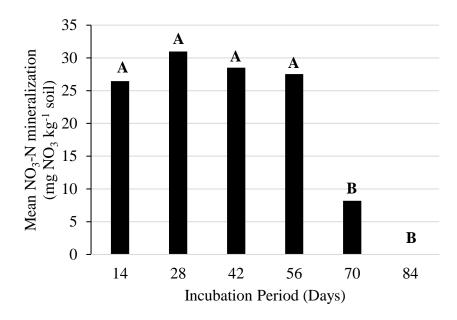


Figure A34. NO<sub>3</sub>-N mineralization mean patterns, for the bare, unamended soil, over six incubation periods time for the fifth freeze and thaw cycle with significance differences in values indicated among the incubation periods.

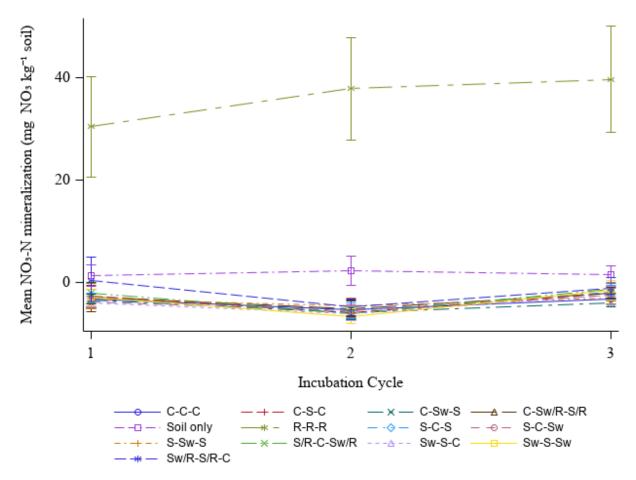


Figure A35. NO<sub>3</sub>-N mineralization mean for twelve crop residue treatments and their rotations for corn (C), soybean (S), spring wheat (SW), and radish (R), plus an untreated soil control over three incubations and two freeze and thaw cycles in the Forman soil series in North Dakota.

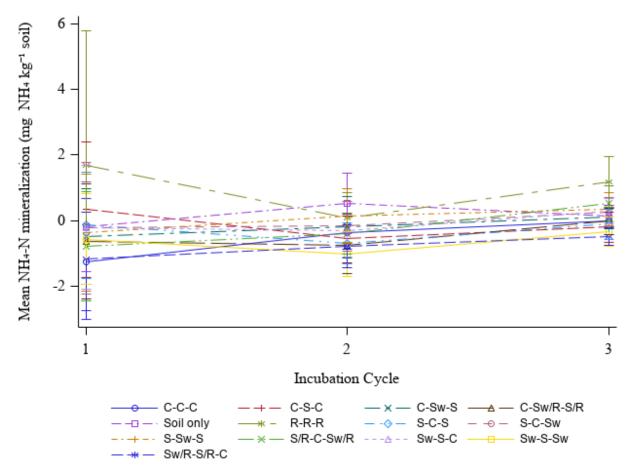


Figure A36. NH<sub>4</sub>-N mineralization mean for twelve crop residue treatments and their rotations for corn (C), soybean (S), spring wheat (SW), and radish (R), plus an untreated soil control over three incubations and two freeze and thaw cycles in the Forman soil series in North Dakota.

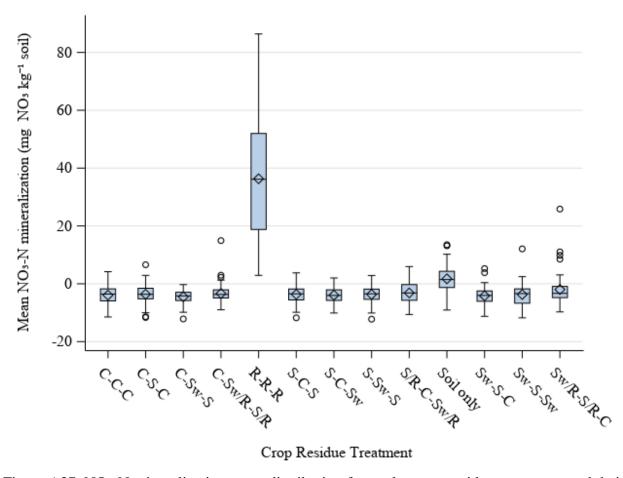


Figure A37. NO<sub>3</sub>-N mineralization mean distribution for twelve crop residue treatments and their rotations for corn (C), soybean (S), spring wheat (SW), and radish (R), plus an untreated soil control over three incubations and two freeze and thaw cycles in the Forman soil series in North Dakota.

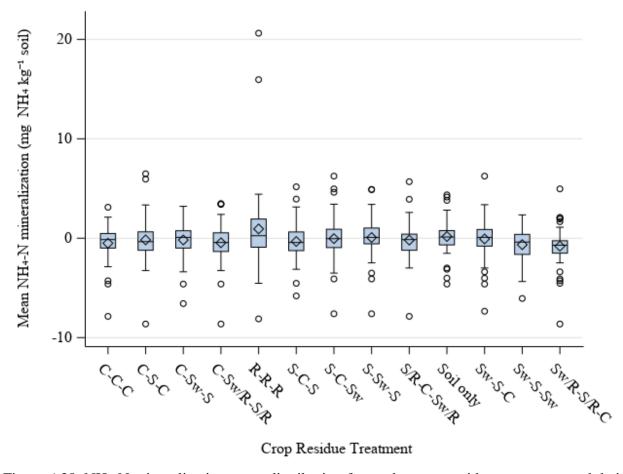


Figure A38. NH<sub>4</sub>-N mineralization mean distribution for twelve crop residue treatments and their rotations for corn (C), soybean (S), spring wheat (SW), and radish (R), plus an untreated soil control over three incubations and two freeze and thaw cycles in the Forman soil series in North Dakota.

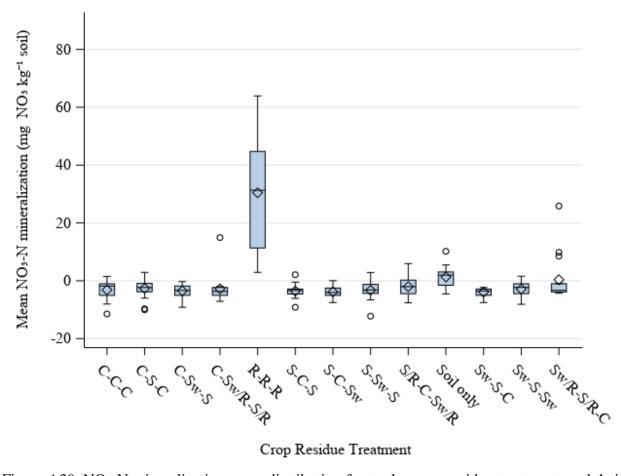


Figure A39. NO<sub>3</sub>-N mineralization mean distribution for twelve crop residue treatments and their rotations for corn (C), soybean (S), spring wheat (SW), and radish (R), plus an untreated soil control for the first incubation series in the Forman soil series.

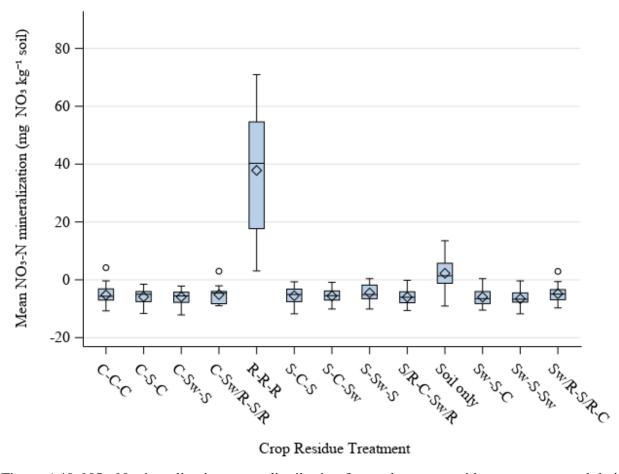


Figure A40. NO<sub>3</sub>-N mineralization mean distribution for twelve crop residue treatments and their rotations for corn (C), soybean (S), spring wheat (SW), and radish (R), plus an untreated soil control following the first freeze and thaw cycle during the second incubation series in the Forman soil series.

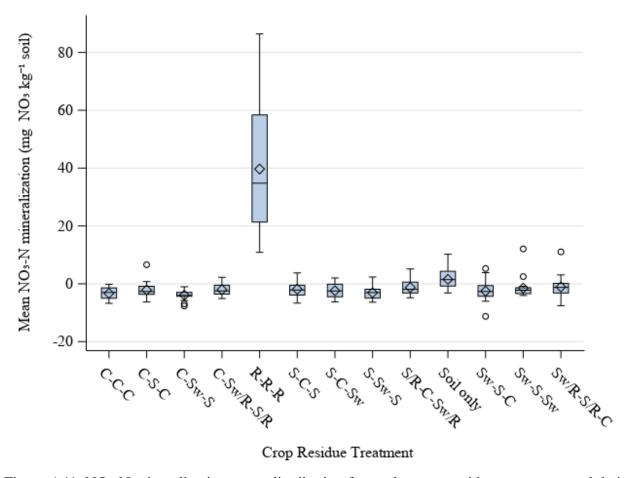


Figure A41. NO<sub>3</sub>-N mineralization mean distribution for twelve crop residue treatments and their rotations for corn (C), soybean (S), spring wheat (SW), and radish (R), plus an untreated soil control following the second freeze and thaw cycle during the third incubation series in the Forman soil series.

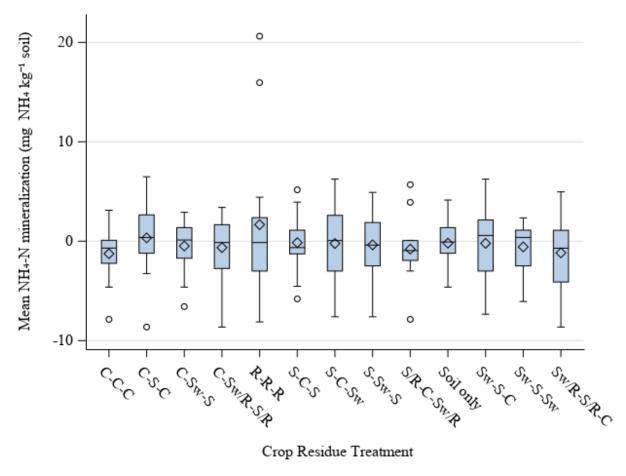


Figure A42. NH<sub>4</sub>-N mineralization mean distribution for twelve crop residue treatments and their rotations for corn (C), soybean (S), spring wheat (SW), and radish (R), plus an untreated soil control during the first incubation series in the Forman soil series.

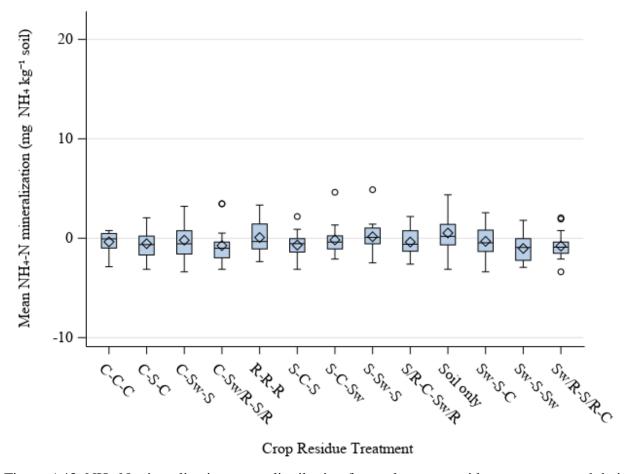


Figure A43. NH<sub>4</sub>-N mineralization mean distribution for twelve crop residue treatments and their rotations for corn (C), soybean (S), spring wheat (SW), and radish (R), plus an untreated soil control following the first freeze and thaw cycle during the second incubation series in the Forman soil series.

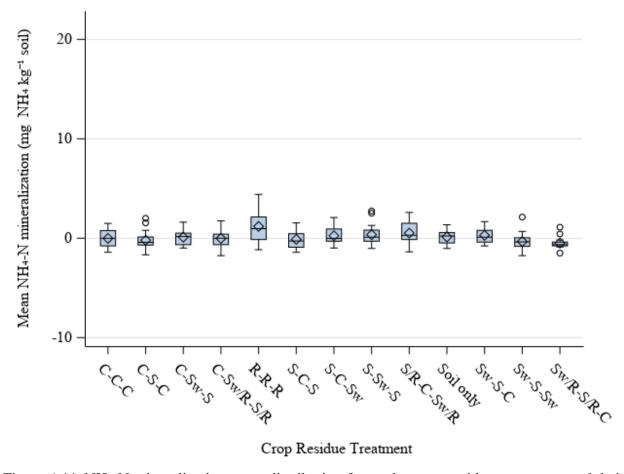


Figure A44. NH<sub>4</sub>-N mineralization mean distribution for twelve crop residue treatments and their rotations for corn (C), soybean (S), spring wheat (SW), and radish (R), plus an untreated soil control following the second freeze and thaw cycle during the third incubation series in the Forman soil series.