IMPROVING NITROGEN MANAGEMENT, INCLUDING THE USE OF COVER CROPS, IN NORTH DAKOTA CROPPING SYSTEMS

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Title

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

DOCTOR OF PHILOSOPHY

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ABSTRACT

Crop production in North Dakota covers nearly 64 million ha, playing a crucial role in the state's economy. However, wide-spread agriculture also poses environmental risks resulting from soil erosion and loss of N to ground and surface water. To address these concerns, agriculturists must adopt practices to decrease soil erosion and responsibly manage N. Between 2020 and 2024, several studies in North Dakota focused on improving N management in two-row malting barley (*Hordeum vulgare* L.), explored opportunities for cover crop integration, and assessed the rotational impact cover crops on crop productivity and soil factors. Research indicated N recommendations ranging from 89 to 190 kg available N ha^{-1} could optimize profitability and barley quality while reducing fertilizer requirements compared to yield-goal based recommendations. Although cover crops planted following barley harvest sequestered N in the biomass preventing leaching, the subsequent two cropping years of corn (*Zea Mays* L.) and wheat (*Triticum aestivum* L.) showed no significant yield response from the cover crop. It did appear the cover crop had an impact on the wheat yield response to N, indicating a potential long-term benefit. In addition to cover crops, managing barley residue resulted in significant soil temperature differences in the spring, with greater mean daily temperatures measured where residue was removed compared to residue-mulched or cover cropped treatments; these temperature differences were attributed to increased absorption of solar radiation. The absence of mulch or cover crops, however, caused greater fluctuations and lower minimum temperature in the bare-soil treatment. Additionally, integrating interseeded cover crops into wide-row (152-cm) corn was determined to be a viable option for adding diversity to the cropping system without impacting corn yield. Through responsibly managed N recommendations in North Dakota

cropping systems, dependence on N fertilizers can be reduced. The integration of cover crops can sequester N and provide erosion control without a significant impact on rotational crop yield.

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DEDICATION

This dissertation is dedicated to farmers past, present, and future who cultivate the land not for personal gain, but because they are called to be farmers by inborn attachment to the earth. Their dedication resonates through generations, as they strive to improve the land, replace what they have taken, and conserve it for the future. Their commitment embodies a profound understanding of stewardship, supporting both our environment and our communities.

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LIST OF ABBREVIATIONS

DOY ....Day of the year

EONR..Economic optimum nitrogen rate

TKAN ....Total known available nitrogen

UAN..Urea ammonium nitrate

WSA..Water stable aggregates

LIST OF SYMBOLS

a..Regression coefficient–quadratic

AE ....Available energy

b..Regression coefficient–slope

c..Regression coefficient–intercept

$C_{mineral}$..Heat capacity of mineral matter

C_{om} ....Heat capacity of organic matter

C_{soil} ....Specific heat capacity of the soil

C_{soild}...Heat capacity of soil solids

C_{w}...Heat capacity of water

G...Soil heat flux

G_{6cm} ....Soil heat flux at 6 cm depth

H...Sensible heat flux

$L_{absorbed}$ ....Long wave solar radiation absorbed

LE...Latent heat flux

$L_{emitted}$ ....Long wave solar radiation emitted

N_{Fert} ....Fertilizer N

N_{PC} ....Prior crop N credits

N_{S} ....Preplant soil NO_3-N

N_{TC} ....No-tillage N credits

P_{b}...Price of barley

P_{n}...Price of N fertilizer

R_{n}...Net solar radiation

$S_{absorved}$..Short wave solar radiation absorbed

$S_{emitted}$ ....Short wave solar radiation emitted

TC ....Total cost

TR ....Total return

ΔS..Change in soil energy storage

ΔT..Change in temperature

Δt..Change in time

Δz ....Change in depth

θ_g ....Soil gravimetric water content

θ_v ....Soil volumetric water content

ρ_b ....Soil bulk density

$\Phi_{mineral}$ ....Fraction of mineral matter

Φ_{om} ....Organic matter

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1. GENERAL INTRODUCTION

1.1. North Dakota Agriculture

With over 64 million ha of land in crop production, agriculture is one of the leading sectors in North Dakota industry (Bangsund and Hodur, 2022; USDA-NASS, 2024b). Ranking first in the nation in the production of wheat (*Triticum aestivum* L.), oats (*Avena sativa* L.), cereal rye (*Secale cereale* L.), sunflower (*Helianthus annuus* L.), canola (*Brassica napus* L.), flax (*Linum usitatissimum* L.), and pinto bean (Phaseolus vulgaris L.), and second in the production of barley (*Hordeum vulgare* L.), dry edible peas (*Pisum sativum* L.), lentils (*Lens culinaris* Medik), and sugarbeet (*Beta vulgaris* L.) (Jantzi et al., 2023), the diversity of crops contribute greatly to the $30.8 billion yearly economic impact agriculture has on the North Dakota economy (Bangsund and Hodur, 2022). However, this productivity does not come without a cost to the soil of North Dakota; based on 2017 estimates, 12.3 Mg ha^{-1} of soil is lost yearly to wind erosion across the state (USDA, 2020). Not only does this erosion come at a direct financial cost to North Dakota producers in terms of lost fertility (Franzen, 2021), but also causes ecological and environmental damage resulting from sedimentation of surface water with nutrient-rich soil (Cihacek et al., 1993; Capel et al., 2018) and loss of productivity from land degradation (Lal, 1993). With applications of fertilizer and other soil amendments costing North Dakota producers approximately $1.5 billion per year (USDA-NASS, 2024a), it is essential to ensure nutrient use efficiency is maximized through proper application of fertilizer, conscious management of residual nutrients, and field management practices to minimize off-field movement of soil and nutrients.

1.2. Implications of Nitrogen Fertilization

Based on estimates from the Food and Agriculture Organization of the United Nations, (2019), N fertilizer is in the greatest demand and highest usage rate of all applied synthetic fertilizers by farmers. According to previous research, however, N use efficiency (NUE) ranges only from 30-53% across production systems (Conant et al., 2013; Lassaletta et al., 2014; Anas et al., 2020; Mălinaş et al., 2022; Govindasamy et al., 2023) indicating one or more causes of reduced NUE: inefficient uptake of N by the crop, excessive application rates, or losses due to denitrification, immobilization, volatilization or leaching.

Besides economic concerns surrounding low NUE (Langholtz et al., 2021), the environmental impacts of N losses are far reaching, impacting groundwater, surface water, and the atmosphere (Power and Schepers, 1989; Castro et al., 2003; Bock, 2015; Capel et al., 2018; Langholtz et al., 2021). Fortunately, N losses can be reduced or minimized through the adoption of improved agronomic practices such as optimizing N rates (Anas et al., 2020), utilizing products to decrease volatilization and nitrification (Franzen, 2022), and implementing practices to capture residual N to prevent losses. Integrating cover crops, for example, have been shown to reduce NO_3-N levels following crop production decreasing the opportunity for leaching (Tonitto et al., 2006; Ketterings et al., 2015; Lee et al., 2016; Hanrahan et al., 2018).

1.3. Cover Crop Opportunities and Barriers

A cover crop is a grass or forb grown for the primary purpose of seasonal soil protection, soil improvement, or conservation and is (USDA-NRCS, 2010). In addition to sequestering N, cover crops have also been shown to reduce soil erosion by providing the necessary cover to protect the soil following low-residue crops, removal of crop residue, or when used in place of a fallow period (Kaspar et al., 2001; Blanco-Canqui et al., 2015). With a living plant in the soil for a longer period, the additional root exploration and added plant diversity, cover crops may also and improve soil health factors including aggregate stability, infiltration, and microbial diversity (Chan and Heenan, 1999; Blanco-Canqui et al., 2015; Mitchell et al., 2017; Ghimire et al., 2019).

Although the benefits of cover crops have been demonstrated, there are still multiple barriers to adoption including lack of measured economic return, yield reduction in subsequent crops, and increased time and labor for management (CTIC et al., 2023). Additionally, in North Dakota and other areas with short growing seasons, the opportunities for sowing cover crops are limited following many of the major commodity crops, particularly corn (*Zea Mays* L.) and soybeans (*Glycine max* L.). Previous research has resulted in mixed yield responses for crops grown following cover crops ranging from yield gains (Andraski and Bundy, 2005; Reinbott et al., 2004; Muramoto et al., 2011; Blanco-Canqui et al., 2012; Snapp and Surapur, 2018), to opposite, mixed, or neutral effects (Kuo and Jellum, 2000; Kuo et al., 2001; Fageria et al., 2005; O'Reilly et al., 2012; Berti et al., 2017; Ruark et al., 2018; Ghimire et al., 2019; Andersen et al., 2020; Leiva, 2020). With uncertainty surrounding the rotational effects of cover crops, producers are hesitant to adopt them into their production systems (CTIC et al., 2023).

1.4. Dissertation Format

To address concerns regarding N fertilizer usage, residual soil N, and the implications of cover crop growth, opportunities for improved N-fertilizer recommendations, viable timings for cover crop integration, and the rotational impact of cover crops on crop yield and N dynamics need to be explored. Through a collection of five studies, this dissertation aims to provide insight into methods which may be utilized to improve the cropping systems of North Dakota farmers beginning first with a study developing N recommendations for two-row malting barley. The approach used in this study removes crop yield as a factor in fertilizer rate and focuses on efficiency and profitability. By accounting for inputs of N from multiple sources and fertilizing at a rate of maximum NUE, costs to producers can be reduced and residual N decreased. Following barley harvest is an ideal opportunity for sowing a cover crop; therefore, the second study focuses on the productivity of the mixed-species cover crop following barley and quantifies its impact on soil aggregate stability and NO_3-N sequestration. The necessity to understand the implications of cover crops on other crops in the rotation is the impetus for the remaining three studies. The rotational effect of cover crops on N availability and subsequent crop yield are analyzed in the third study along with the dynamics of soil NO_3-N, NH_4-N, and non-exchangeable NH_4-N pools. Concerns regarding the impact of cover crops on soil warming and moisture dynamics in the spring are addressed in the fourth study using an energy balance approach. Lastly, the fifth study explores and opportunity for integrating cover crops into a corn grain system and the impact on grain yield.

Two of the five chapter presented in this dissertation have been previously published: Managing Nitrogen to Promote Quality and Profitability of North Dakota Two-row Malting Barley (Goettl et al., 2024b) and Interseeding Cover Crops in Wide-Row Corn (Goettl et al., 2024a). To ensure continuity with these published works, the remaining chapters are formatted using the guidelines set forth by the American Society of Agronomy.

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2. MANAGING NITROGEN TO PROMOTE QUALITY AND PROFITABILITY OF NORTH DAKOTA TWO-ROW MALTING BARLEY[1,2]

2.1. Abstract

As the demand and cultivation of two-row malting barley (*Hordeum vulgare* L.) increases in the Northern Great Plains, updated nitrogen (N) recommendations are increasingly necessary. Not only does N play a role in grain yield, but it also impacts grain malting characteristics, including protein and kernel plump. To determine the impacts N rate and availability have on two-row malting barley, two experimental sites were established in eastern North Dakota during the 2020 and 2021 growing seasons. Treatments consisted of five fertilizer rates from 0 to 180 kg N ha^{-1} and two malting barley cultivars. Soil samples to be analyzed for nitrate-N were taken prior to planting and N credit estimates from the previous crop were considered to determine the total known available nitrogen (TKAN) in the soil. It was determined there was a strong relationship between N rate and grain yield along with a strong positive correlation between N rate and grain protein. No significant interactions between N rate and kernel plump were noted. When the relationship between relative grain yield and TKAN was modeled using a best-fit regression, maximum yield was attained at 210 kg TKAN ha^{-1} with a grain protein of 128 g kg^{-1}, meeting malting quality requirements. When factoring in grain value and cost of urea fertilizer, the TKAN range needed to produce the crop at the highest profitability was lower than TKAN of maximum yield, ranging from 89 to 190 kg TKAN ha^{-1}.

[1]The material in this chapter was co-authored by Brady Goettl, Thomas DeSutter, Honggang Bu, Abbey Wick, and David Franzen. Brady Goettl had primary responsibility for conducting field work and collecting samples. Brady Goettl was the primary developer of the conclusions that are advanced here. Brady Goettl also drafted and revised all versions of this chapter. Thomas DeSutter and David Franzen served as proofreaders and checked the math in the statistical analysis conducted by Brady Goettl.

[2]Goettl, B., DeSutter, T., Bu, H., Wick, A., & Franzen, D. (2024). Managing nitrogen to promote quality and profitability of North Dakota two-row malting barley. *Agronomy Journal*, 1–8. https://doi.org/10.1002/agj2.21538

2.2. Introduction

The Northern Great Plains region—specifically North Dakota, Montana, and southern Manitoba and Saskatchewan—are large producers of barley. Historically, the barley cultivars in this region destined for the malting industry were six-row types; however, very recently, malting companies began to contract only two-row barley cultivars, leading to a shift in production. Of the 41 malting barley cultivars currently recommended by the American Malting Barley Association, 34 of them are two-row types (American Malting Barley Association, 2023a). One of the reasons behind this change in preference from six-row to two-row barley for malting is the generally lower grain protein content (Franzen & Goos, 2019; McKenzie et al., 2005). Barley with lower protein content results in more rapid water uptake during malting, which allows the grain to progress through the process more quickly (Hertsgaard et al., 2008), decreasing malting costs. Additionally, the high protein content in the malt produces problems during beer fermentation, generating cloudiness in the final product. McKenzie et al. (2005) asserted nitrogen (N) fertilization is the most important factor in malting barley production since N in excess of what is required for yield increases grain protein (Lauer & Partridge, 1990). Accurate determination of N rate for two-row barley is essential not only to maximize yield potential while controlling cost and overapplication of fertilizer, but also to meet the strict grain quality requirements of the maltsters, who are the primary buyers of this commodity (Franzen & Goos, 2019). There is an established correlation between N fertilization and percentage of plump kernels, protein content, and test weight, malting quality factors established by maltsters (Lauer & Partridge, 1990; McKenzie et al., 2005; O'Donovan et al., 2015). Although specific quality requirements vary among maltsters, the American Malting Barley Association sets the ideal criteria for two-row barley as follows: protein content <130 g kg^{-1} and >90% plump kernels retained on a 2.38 mm sieve (American Malting Barley Association, 2023b). Two of the most common reasons for malting barley rejection are high protein content and a low percentage of plump kernels. The consequence of grain rejection by maltsters is very severe; feed barley is often priced about half the value of malting grade. Studies indicate a positive relationship between N rate and grain protein (Lauer & Partridge, 1990; McKenzie et al., 2005; O'Donovan et al., 2015). Additionally, a minor inverse relationship between grain protein content and kernel plump has been reported (Baethgen et al., 1995; Clancy et al., 1991; McKenzie et al., 2005). In some cases, the supplemental N rate needed to attain maximum grain yield is greater than the N rate at which grain quality is within the optimum range. Baethgen et al. (1995) stated a balance must be found between obtaining profitable yield for malting barley and meeting quality requirements. This balance between yield and quality should also consider N use efficiency. As a result, grain could be produced at a yield which maximizes economic returns for the farmer, meets malting quality requirements, and minimizes residual soil nitrate-N following harvest. The purpose of this study was to determine the rate of available N, which will maximize profitable yield and optimize grain quality characteristics for two-row malting barley in the Northern Great Plains.

2.3. Materials and Methods

2.3.1. Site Descriptions

These on-farm experiments took place during the 2020 and 2021 growing seasons, with two experimental sites each year. In total, four site-years of data were generated on non-irrigated, no-till locations in Grand Forks and Barnes Counties in North Dakota, near Logan Center (LC) and Valley City (VC), respectively (Table 2.1).

Table 2.1. Soil properties and chemical analyses for each experimental location, measured prior to barley seeding. NO_3-N was sampled to a depth of 60 cm while P, K, pH, and organic matter were sampled to a depth of 15 cm.

Environment[a]	**Series**	**Texture**	**NO_3-N**	**P**	**K**	**pH**	**OM**
			kg ha^{-1}	mg kg^{-1}	mg kg^{-1}		g kg^{-1}
VC2020	Swenoda[b]	sandy loam	43	27	201	5.2	26
LC2020	Barnes[c]	loam	47	15	282	6.7	39
VC2021	Barnes	loam	49	23	67	5.1	22
LC2021	Barnes	loam	60	25	207	5.6	52

[a]Sites were located near Logan Center (LC) or Valley City (VC), North Dakota
[b]Coarse-loamy, mixed, superactive, frigid Pachic Hapludolls (Soil Survey Staff, 2023)
[c]Fine-loamy, mixed, superactive, frigid Calcic Hapludolls (Soil Survey Staff, 2023)

Both experiments at the VC site had been under no-till management for over 40 years, producing several rotational crops including corn, soybean, oil-seed sunflower, six-row malting barley, and hard red spring wheat. The previous crop at the 2020 VC site (46.88403N, 97.915529W) was oil-seed sunflowers, with corn being previously grown in another VC site in 2021 (46.880486N, 97.913760W).

The LC sites in 2020 (47.795544N, 97.773766W) and 2021 (47.791001N, 74 97.775661W) were transitioned to no-till management <5 years before the establishment of the experiment. Crops in rotation consisted of pinto bean, soybean, six-row malting barley, and hard red spring wheat. The previous crop on the LC sites was pinto bean in 2020 and 2021.

Weather conditions in 2020 varied greatly from 2021, most notably in terms of precipitation (Table 2.2). At the LC location, April–July precipitation was 6.5 mm above normal in 2020 and in 2021 precipitation was 158 mm below normal (NDAWN, 2023). Similar lack of in-season rainfall was recorded at the VC sites; April–July precipitation was 31.2 mm above normal in 2020 and 167 mm below normal in 2021 (NDAWN, 2023).

Table 2.2. Average air temperature and total precipitation at two sites in North Dakota based on 30-yr average and their departure from the average for each growing season, as reported by the North Dakota Agricultural Weather Network (NDAWN, 2023).

		Site[a]			
		LC		**VC[b]**	
Year	**Month**	**30-yr Average**	**Departure from 30-yr Average**	**30-yr Average**	**Departure from 30-yr Average**
	Average Air Temperature				
		°C			
2020	Apr.	4.2	-2.4	5.6	-2.5
	May	12.1	-1.3	13.2	-1.6
	June	17.8	2.2	19.0	2.0
	July	20.2	1.1	21.4	1.0
	Aug.	19.2	0.2	20.3	0.0
2021	Apr.	4.2	0.2	5.6	-0.4
	May	12.1	-0.3	13.2	-0.3
	June	17.8	3.3	19.0	2.9
	July	20.2	2.4	21.4	1.6
	Aug.	19.2	1.0	20.3	0.9
	Total Precipitation				
		mm			
2020	Apr.	27.7	-7.5	35.6	-13.5
	May	75.2	-38.9	81.0	-43.9
	June	95.5	43.0	94.5	19.6
	July	93.5	9.9	79.0	68.9
	Aug.	68.8	-49.3	65.0	25.0
2021	Apr.	27.7	-15.3	35.6	-12.7
	May	75.2	-35.0	81.0	-61.7
	June	95.5	-43.4	94.5	-22.0
	July	93.5	-65.2	79.0	-71.1
	Aug.	68.8	29.2	65.0	13.3

[a]Sites were located near Logan Center (LC) or Valley City (VC), North Dakota
[b]Data from the Fingal, ND weather station, approximately 14.5 km from the VC site.

2.3.2. Experimental Design

The independent variables in this experiment consist of five N fertilizer treatments within two cultivars of two-row barley. The N treatments ranged from 0 to 180 kg ha^{-1} in 45 kg increments (0, 45, 90, 135, and 180 kg ha^{-1}), which spans the range above and below current N recommendations for two-row barley. The two cultivars used in this experiment were ND Genesis and AAC Synergy, which are two-row malting barley cultivars recommended by the American Malting Barley Association (2023a). ND Genesis was released in 2015 by North Dakota State University and AAC Synergy in 2015 by Syngenta seeds (Keene et al., 2021; Ransom et al., 2019, 2020). Each experimental unit was 2.4 m wide by 12.2 m long and plots were organized in a randomized complete block design with a split-plot arrangement, with cultivar as the main plot and N rate as the sub-plots. In 2020, the treatments were replicated 10 times, producing 100 experimental units at each site. The number of experimental units was reduced by 50% in 2021, consisting of five replications for a total of 50 experimental units at each site.

2.3.3. Nitrogen Management

To determine the optimum N rate for a crop, fertilizer N is only one factor considered in North Dakota State University Extension recommendations; the total known plant available N (TKAN) from all known sources should be considered for profitable and environmentally responsible N management. To determine TKAN, preplant soil NO_3-N (N_S) was added to crop N credits (N_{PC}), no-tillage N credits (N_{TC}), and amount of fertilizer N applied (N_{Fert}) (Eq 2.1) (Clark et al., 2020; Franzen, 2023; Hergert, 1987; Schultz et al., 2018).

$$\text{TKAN} = N_{PC} + N_{TC} + N_S + N_{\text{Fert}} \tag{2.1}$$

Previous crop N credits, reported in Franzen (2023), include a 44.8 kg N ha^{-1} credit for previous crops of soybean, edible bean, and other legume crops. A 44.8 kg N ha^{-1} credit is assessed in systems in no-till management for >6 years, systems in transitional or intermittent no-till are penalized 22.4 kg N ha^{-1}, conventional systems receive no N credit or reduction (Franzen, 2023). Preplant soil NO_3-N tests were obtained from soil cores extracted from a depth of 0–60 cm across each replication and processed by NDSU Soil Testing Lab (Fargo, ND) and Agvise Laboratories (Northwood, ND) using an H_2O extractant method (Franzen, 2023; Nathan & Gelderman, 2012).

In 2020, the sum of soil NO_3-N (N_S), N credits from previous crops (N_{PC}), and tillage (NTC) ranged from 58.3 up to 94.2 kg N ha^{-1} across research sites and transects; in 2021, the range was from 71.7 to 94.2 kg N ha^{-1}. In 2020 and 2021, the LC site received a 44.8 kg N ha^{-1} credit from the previous crop of pinto beans but was penalized 22.4 kg ha^{-1} for being in the transitional no-till stage (Franzen, 2023). No previous crop credits were assessed at the VC site, but a 44.8 kg ha^{-1} long-term no-till N credit was added each year (Franzen, 2023).

At planting, N fertilizer was hand-broadcast applied to the specific treatments using pre-weighed SUPERU (46% N) as the fertilizer N source. SUPERU is a urea-based fertilizer treated with dicyandiamide (DCD) and N-(n-butyl) thiophosphoric triamide (NBPT), which are a nitrification inhibitor and urease inhibitor, respectively (Koch Agronomic Services LLC, 2021). Additionally, 112 kg ha^{-1} of pelletized gypsum (calcium sulfate, 20% sulfur [S]) was broadcast applied at the time of N application to ensure that S deficiency did not confound N response.

2.3.4. Crop Management

Barley was no-till drilled on May 6, 2020, at both the LC and VC sites, on April 5, 2021, at the VC site, and on April 6, 2021, at the LC site. At all sites, the barley was sown in 19-cm rows at the seeding rate of 3.08 million seeds ha^{-1} using a John Deere 1890 No-Till Air Drill (Deere and Co.). In-furrow fertilizer (12% N, 40% P2O5, 4% Zn) was used on both of the 2021 sites at the rate of 84 kg ha^{-1} at VC and 112 kg ha^{-1} at LC (Franzen & Goos, 2019). In-season crop and pest management was uniformly completed by the cooperating farmers. At the LC site, 1.1 L ha^{-1} of MCPA Ester, 1.4 L ha^{-1} of WideMatch (Corteva Agriscience), and 1.1 L ha^{-1} of Axial Bold (Syngenta Crop Protection) were applied post emergence to control weeds, with 1.0 L ha^{-1} Caramba Fungicide (BASF Corporation) applied at heading to control disease. At the VC site, 1.4 L ha^{-1} Cleansweep (Nufarm Inc.) herbicide and 146 mL ha^{-1} Tilt (Syngenta Crop Protection) fungicide were applied post emergence.

Grain was directly harvested on August 10, 2020, at the VC site and on August 18, 2020, at LC, August 5, 2021 at VC, and August 11, 2021, at LC using a plot combine (ALMACO). To limit edge interaction from N movement among the treatments, only the center 1.52 m of each experimental unit was harvested. Grain was collected in breathable cloth bags and transported to the laboratory for all post-harvest measurements and quality analyses.

2.3.5. Data Collection and Lab Analysis

The harvested, field moist, grain samples were placed into convection dryers at 60°C for 12 h prior to processing. Samples were weighed and then cleaned using a Clipper Model-2B cleaner (A.T. Ferrell Co.) to improve grain for further analysis.

Grain moisture and test weight were measured using a Dickey–John model GAC500 XT grain analyzer (Dickey–John). Grain harvest weights were adjusted to the standard moisture content of 13.5% for yield calculations. Quality measurements were conducted by the NDSU Barley Quality Laboratory. Quality relating to kernel size was determined by sieving. Percent plump kernels were considered as the percent of kernels, by weight, which do not pass through a

2.38-mm sieve (American Malting Barley Association, 2023b). Grain protein content was determined using the FOSS Infratec 1241 Grain Analyzer (FOSS).

2.3.6. Statistical and Economic Analysis

Data analysis was performed using SAS 9.4 and JMP (SAS Institute). Analysis of variance was carried out as randomized complete block design with a split plot arrangement using SAS PROC MIXED. Year and location were combined into one source of variation, environment, and considered a random effect. Replication was analyzed as a random effect and barley cultivar and N rate as fixed effects. Data were tested for homogeneity of variance using Bartlett's chi-square test. Regression analysis was performed using JMP nonlinear modeling. Data in this study were considered statistically significant at $p \leq .05$.

Recognizing the independence of actual crop yield and N rate (Raun et al., 2011; Vanotti & Bundy, 1994), the approach used in this study relies on the strong relationship between relative (also referred to as standardized or normalized) yield and TKAN (Franzen et al., 2021). Relative yield was calculated by dividing the yield of each experimental unit by the maximum yielding experimental unit at each site. For the development of the N recommendation, mean TKAN and yield within each N rate treatment for each environment was calculated. Relative yield was then determined within each environment and regressed against TKAN. For economic analysis, the relative yield was then multiplied by the average yield to convert the proportion back to kg ha^{-1}. The economic optimum nitrogen rate (EONR) for two-row malting barley was calculated based on the relationship between barley price (P_b) and the cost of N fertilizer (P_n) (Nafziger et al., 2004; Sawyer et al., 2006). The relative grain yield regression coefficients (a, b, and c) from the yield-to-TKAN comparison were used in Equation 2.2 to calculate EONR at various barley and N fertilizer costs (Fausti et al., 2018).

$$\text{EONR} = \frac{P_n}{P_b} \times \frac{1}{2a} - \frac{b}{2a} \quad (2.2)$$

$$\text{TC} = (N)P_n \quad (2.3)$$

$$\text{TR} = [aN^2 + bN + c]P_b \quad (2.4)$$

Total cost (TC) related to N input (N) and Pn was calculated using Equation 2.3. Total return (TR) was calculated as yield as a function of N multiplied by P_b (Eq 2.4). Net return was then calculated as the difference between TR and TC.

2.4. Results and Discussion

2.4.1. Grain Yield and Quality

No statistical differences were noted between the two barley varieties for any of the parameters measured in this study (Table 2.3). It was determined the relationship between N rate and grain yield was significant (Table 2.3). Grain protein content also showed a highly significant positive relationship with N rate, a relationship previously established by Lauer and Partridge (1990), McKenzie et al. (2005), and O'Donovan et al. (2015). No significant interactions between the N rate and kernel plump or test weight were noted at the N rates applied in this experiment. Previous studies note an interaction between N rate and kernel plump (Baethgen et al., 1995; Clancy et al., 1991; Jackson, 2000; McKenzie et al., 2005; Weston et al., 1993); additionally, precipitation/irrigation during the growing season has also been noted to impact this trait (Rogers, 2022; Stevens et al., 2015). Cause for lack of kernel plump response in this study is not clear; however, average plump and test weight in this study are within malting quality requirements, an outcome favorable to producers in the region (American Malting Barley Association., 2023b). The sum of N_S, N_{PC}, and N_{TC} ranged from 58.3 to 94.2 kg ha^{-1} across all environments, preventing any severe N deficiency from occurring.

Table 2.3. Mean values and standard deviation for barley yield, grain protein content, kernel plump, and test weight averaged across four eastern North Dakota environments.

Effects	Variables	Yield	Relative Yield[a]	Protein	Plump	Test weight
		kg ha^{-1}		g kg^{-1}	g g^{-1}	kg m^{-3}
Variety (V)	Synergy	3,490±1,620	0.66±.25	116±15	0.94±.04	587±20
	Genesis	3,180±1,470	0.61±.23	120±23	0.94±.04	593±26
	P-value	NS	NS	NS	NS	NS
N Rate (N)	0 kg ha^{-1}	2,340±900 a	0.46±.16 a	107±16 a	0.93±.04	582±25
	45 kg ha^{-1}	3,150±1,270 ab	0.61±.20 ab	113±21 b	0.94±.04	586±25
	90 kg ha^{-1}	3,700±1,610 b	0.70±.24 b	119±19 c	0.94±.04	594±21
	135 kg ha^{-1}	3,750±1,690 b	0.71±.26 b	124±18 d	0.94±.04	593±22
	180 kg ha^{-1}	3,760±1,670 b	0.71±.24 b	127±18 d	0.93±.04	594±21
	P-value	*	*	***	NS	NS
V x N	P-value	NS	NS	NS	NS	NS

Note: Means with the same letter within column are not significantly different at the 0.05 probability level.
Abbreviation: NS, nonsignificant
[a]Relative yield is calculated as the maximum yield divided by each experimental unit within individual environments.
*, **, *** Significant at the .05, .01, and .001 probability levels

2.4.2. Economic Optimum Nitrogen Rate

When relative grain yield is plotted against TKAN and fitted with polynomial trendline (r^2 = 0.66), maximum potential yield is realized at 210 kg TKAN ha^{-1} (Figure 2.1). As a comparison, when actual (non-normalized) yield is plotted against TKAN, r^2 = 0.04, further supporting the independence of yield and N rate (Franzen et al., 2021). The relationship between grain protein content and TKAN was modeled using a linear regression (r^2 = 0.29) (Figure 2.2); using the linear equation, grain protein content at 210 kg TKAN ha^{-1} is 128 g kg^{-1}. Since the data show the grain protein content is, on average, below the maximum malting content of 130 g kg^{-1} at the TKAN of maximum yield, EONR was calculated without any limitations put in place based on grain protein content.

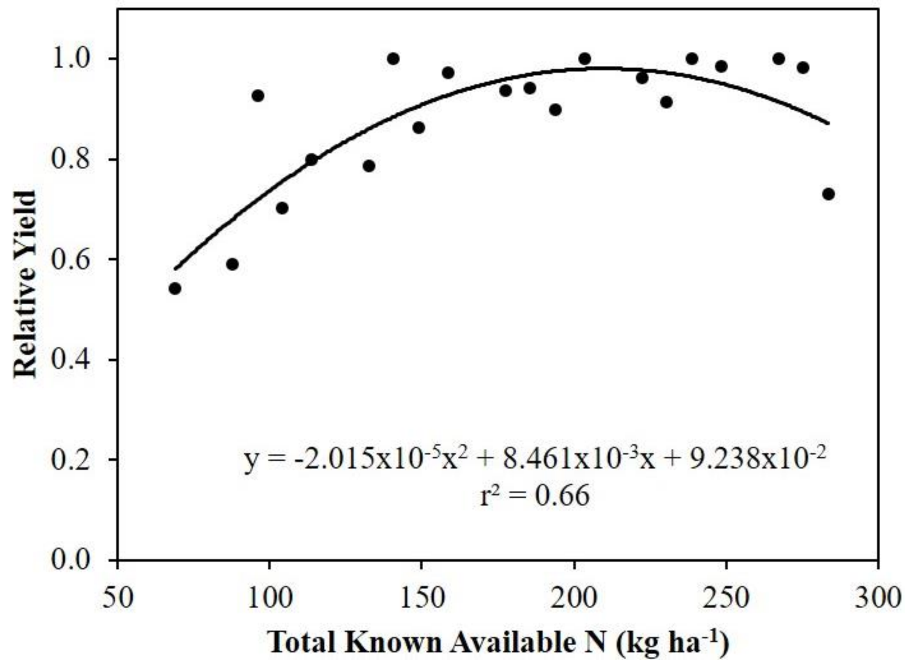

Figure 2.1. Relative two-row barley yield data averaged across replications and varieties at four eastern North Dakota sites compared to total known available nitrogen, fitted with a quadratic trendline.

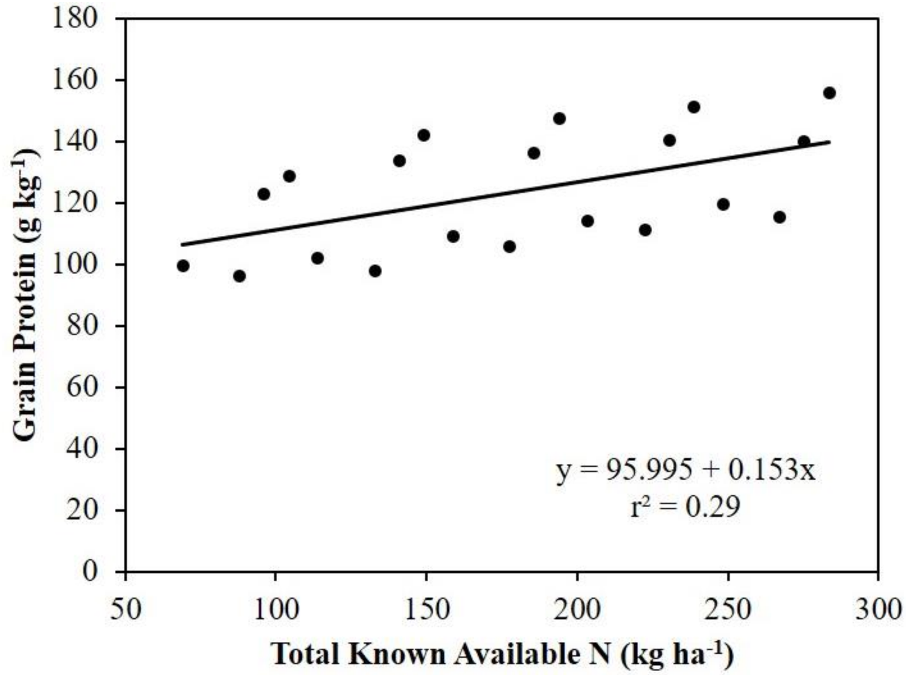

Figure 2.2. Two-row barley grain protein content averaged across replications and varieties at four eastern North Dakota sites compared to total known available nitrogen, fitted with a linear trendline.

Within normal economic ranges in North Dakota, barley prices from \$160 to \$300 Mg^{-1} and N fertilizer prices between \$0.60 and \$2.60 kg N^{-1}, the maximum EONR is 195 kg N ha^{-1} (at \$300 Mg^{-1} barley and \$0.60 kg^{-1} N). As barley price decreases, N cost increases, or both, the ratio between N cost and barley price (N:barley) becomes larger, indicating tighter potential margins and thus promoting lower N rates. The benefit of calculating N rate based on the EONR method is to attain maximum economic return at higher N:barley price ratios without the necessity of fertilizing to maximum yield (Figure 2.3).

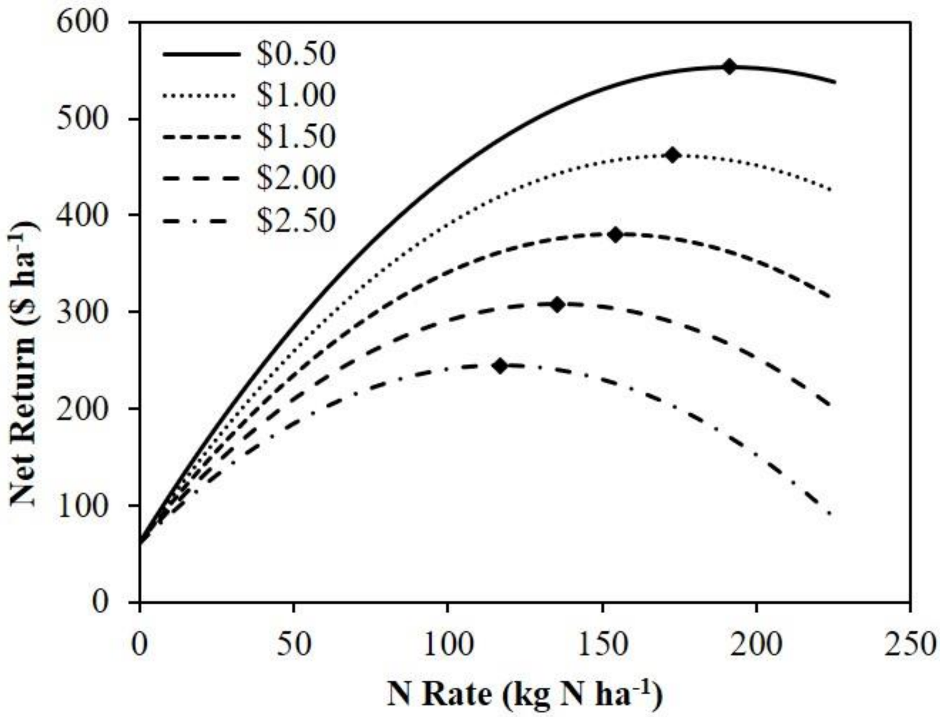

Figure 2.3. Comparison of economic optimum nitrogen rates for two-row malting barley in eastern North Dakota and potential net return with barley price at \$200 Mg^{-1} and nitrogen (N) costs at \$0.50, \$1.00, \$1.50, \$2.00, and \$2.50 kg^{-1}.

2.4.3. Management Implications

By approaching N recommendations and crop production from the standpoint of maximizing crop profitability in place of maximizing yield, not only will the probability of increased net return be realized, but the amount of N fertilizer will also be reduced. The TKAN approach encourages farmers to credit and utilize pre-plant soil N, legume contributed N, and tillage system N, thereby reducing the amount of synthetic N needed to balance the recommendation. Furthermore, the EONR calculation promotes producing a crop at optimal N use efficiency and limits financial and N waste according to the law of diminishing returns (Ferreira et al., 2017). Further refinement of the EONR recommendation can be attained by grouping N rate experiments based on geographic location, soil type, or drainage class, among other variables.

2.5. Conclusion

Results from four site-years of data collected in this study support previous findings regarding the amount of N available to the plant as a driver of grain yield and protein content in two-row malting barley. No relationship was noted between N rate and kernel plump or test weight. Regression analysis of grain yield and TKAN determined maximum grain yield was attainable at 210 kg TKAN ha^{-1}. Additionally, when fertilized at the rate of maximum yield, grain protein content averaged 128 g kg^{-1}, which is below the 130 g kg^{-1} standard maximum protein content for malting (American Malting Barley Association, 2023b). When factoring in economic information, the TKAN range needed to produce the barley crop at the highest profitability is lower than TKAN of maximum yield. It should be noted, weather conditions have a great impact on crop yield and quality, specifically grain protein content. Severe drought conditions may cause grain protein content to increase in excess of industry standards at some of the recommended N fertility levels. Additionally, above-average precipitation or temperature fluctuations would likely cause crop responses different than those noted in this study as a result of N leaching, denitrification, or changes in mass flow.

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3. EFFECTS OF COVER CROPS FOLLOWING TWO-ROW MALTING BARLEY ON SOIL NITRATE CONCENTRATION AND AGGREGATION

3.1. Abstract

As the importance of protecting environmental integrity and agricultural sustainability increases, it is essential to implement conservation practices, such as cover cropping, on farm fields. With an average of 38 days in North Dakota between barley harvest and first frost, incorporating barley into a crop rotation provides an opportunity for cover crop planting and beneficial growth before winter. To quantify the impact of cover crops following barley harvest on soil health and N capture, two-row malting barley experiments were established in 2021 at two eastern North Dakota sites. Five N rates (0, 45, 90, 135, and 180 kg N ha^{-1}) were spring-applied to the barley in a randomized complete block design with a split-plot arrangement. Following the barley harvest, mixed species cover crop and no-cover crop treatments were no-till seeded, volunteer barley was allowed to grow with the cover crop and terminated in the no cover crop treatment. Total above-ground dry cover crop biomass ranged from 1610-3270 kg ha^{-1} across the five barley N rates at the end of the growing season, with biomass production increasing with increasing N rate and residual soil NO_3-N. The cover crop treatment reduced soil NO_3-N the end of the growing season compared to the no-cover treatment resulting in 13 and 40 kg N ha^{-1}, respectively. However, the presence of a cover crop did increase the total N residing in the field, from 40 kg N ha^{-1} in the no cover crop treatment, measured as soil NO_3-N, to 76 kg N ha^{-1} in the cover crop treatment, measured as the sum of soil NO_3-N and N in cover crop biomass. Overall, the cover crop reduced soil NO_3-N remaining at the end of the growing season, potentially protecting it from leaching losses as compared to no cover crop, fallow treatments.

3.2. Introduction

Production of crops and livestock for profitable gain is the primary goal of commercial farmers; however, farmers must also concern themselves with land management techniques to address soil erosion, nutrient management, and soil health degradation if long-term production is to be sustained (Hobbs et al., 2008). The management of these factors, aside from their impact on productivity, is crucial for environmental sustainability. By reducing the potential for soil loss due to wind and water erosion, not only is the productivity of cropland protected, but the sedimentation of waterways and nutrient loading leading to surface water eutrophication is also reduced (Capel et al., 2018). To manage erosion, nutrient loss, and soil degradation farmers must continue to adopt environmentally sustainable practices (Lal, 1993). One of these practices is the use of cover crops, which have the ability to capture nutrients on-farm where they can be utilized in future years. By integrating cover crops into their field management systems, farmers would be able to reduce erosion, capture nutrients in the soil profile, increase soil health, and promote biological N_2 fixation (Sarrantonio and Gallandt, 2003; USDA-Natural Resources Conservation Service, 2010). However, the key to integrating cover cropping practices into crop rotations is finding a “window” into which the cover crop will fit (i.e. a time during the growing season when the cover crop can produce enough biomass to be environmentally beneficial) without causing a negative impact on commodity crop production or incurring excessive costs of implementation.

For North Dakota, and other northern regions with short growing seasons, it is neither possible, nor practical, to plant a cover crop following the harvest of most major commodity crops, since killing frosts generally occur before cover crops can adequately grow (Table 3.1). Of the top seven crops produced in North Dakota by area planted, spring wheat, soybean, corn grain, canola, durum (*Triticum durum* L.), dry edible beans, and barley, only three have an average harvest date more than three weeks before the state-wide average first killing frost (Table 3.1) (Jantzi et al., 2020; USDA National Agricultural Statistics Service, 2023). Of these crops, barley has the greatest number of days between harvest and first killing frost, which provides an optimal opportunity to farmers to introduce cover crops into their system to build soil health, control erosion, and capture nutrients.

Table 3.1. Average number of days between the harvest of primary crops and first killing frost in North Dakota.

Crop	**Average harvest date**[a]	**Days between harvest and first killing frost**[b]
Barley	August 18	38
Durum	August 24	33
Spring wheat	August 25	31
Canola	September 8[c]	18
Dry edible beans	September 24	2
Soybean	October 7	0
Corn grain	October 28	0

[a]Median date of most active usual harvesting dates, 20-year average (Jantzi et al., 2020)
[b]Average date of first-2.2°C frost across ND is September 26th (Jantzi et al., 2020)
[c]Average 2014-2020 date of 50% crop harvested (USDA National Agricultural Statistics Service, 2023)

Capturing N remaining in the soil after harvest assists in preventing excess N leaching. If a cover crop is planted following harvest, it has the ability take up residual soil N and store it in its biomass, thus reducing NO_3^- leaching (Lee et al., 2016). In areas where tile drainage is present, the risk of N leaching from the profile is even greater than in un-tiled soils, especially during late winter and spring snowmelt (Hanrahan et al., 2018). When cover crops are grown on tile drained fields, NO_3^- loss can be 69-90 percent less than in fields without cover crops (Hanrahan et al., 2018). Additionally, saturated conditions in undrained or poorly drained soils promote N loss as a result of denitrification. Similarly, in diversified cropping systems using cover crops compared with fallow across the United States and Canada, N leaching was decreased on average by 70 percent (Tonitto et al., 2006).

Additionally, since cover crops are planted during periods when the soil would otherwise be bare, the living plants provide support for soil biological communities (Troch et al., 1999; Finney et al., 2017). The soil communities, in turn, improve soil aggregate stability and water infiltration (Chan and Heenan, 1999; USDA-Natural Resources Conservation Service, 2015). Furthermore, the surface cover of growing cover crops and their carcasses following freeze-up serve to reduce wind and water erosion, thus conserving soil, reducing nutrient loss, and improving soil quality.

As the public importance of protecting environmental integrity and agricultural sustainability increases, it is essential to implement conservation practices such as cover cropping on farm fields. To aid in practical farmer adoption, the cover crop practice should seamlessly integrate into the crop rotation. With an average of 38 days available in North Dakota between barley harvest and first frost, incorporating barley into a crop rotation provides a practical tool for cover crop planting and beneficial growth before winter. The purpose of this study was to quantify the impact of cover cropping practices following two-row barley harvest on soil health and N capture and assess the economic constraints hindering potential adoption.

3.3. Methods and Materials

3.3.1. Site Description

The on-farm experiments took place during the 2021 growing season (See Appendix for information regarding 2020 experiment) at two non-irrigated, no-till experimental sites located in Grand Forks and Barnes Counties in North Dakota, near Logan Center (LC) and Valley City (VC), respectively (Table 3.2). The VC site (46.880486N, 97.913760W) had been under no-till management for over 40 years, producing several rotational crops including corn, soybean, oil-seed sunflower, six-row malting barley, and hard red spring wheat, corn was the previous crop. The LC site (47.791001N, 74 97.775661W) was transitioned to no-till management less than 5 years before the establishment of the experiment. Crops in the LC rotation consisted of pinto bean, soybean, six-row malting barley, and hard red spring wheat. The previous crop on the LC site was pinto bean.

Table 3.2. Soil properties and chemical analyses for each experimental location, measured in April 2021, prior to barley seeding. NO_3-N was sampled to a depth of 60 cm while samples were taken to a depth of 15 cm for P, K, pH, organic matter, and particle size analysis.

Site[a]	**Series**	**Texture**	**NO_3-N**	**P**	**K**	**pH**	**OM**
			kg ha^{-1}	mg kg^{-1}	mg kg^{-1}		g kg^{-1}
VC	Barnes[b]	Loamy Sand	49	23	67	5.1	22
LC	Barnes	Loam	60	25	207	5.6	52

[a]Sites were located near Logan Center (LC) and Valley City (VC), North Dakota
[b]Fine-loamy, mixed, superactive, frigid Calcic Hapludolls (Soil Survey Staff, 2023)

Rainfall during the summer of 2021 was below normal at both sites (NDAWN, 2023) (Table 3.3), leading to decreased barley yields (Goettl et al., 2024). However, rainfall in August was above average (NDAWN, 2023) which supported cover crop germination and biomass accumulation throughout the growth period.

Table 3.3. Average air temperature and total precipitation at two sites in North Dakota based on 30-yr average and their departure from the average for each growing season, as reported by the North Dakota Agricultural Weather Network (NDAWN, 2020)

	Site[a]			
	LC[b]		VC[c]	
Month	**30-yr Average**	**Departure from 30-yr Average**	**30-yr Average**	**Departure from 30-yr Average**
	Air Temperature			
	°C			
Apr.	4.2	0.2	5.6	-0.4
May	12.1	-0.3	13.2	-0.3
June	17.8	3.3	19.0	2.9
July	20.2	2.4	21.4	1.6
Aug.	19.2	1.0	20.3	0.9
Sept.	14.1	2.7	15.3	2.1
Oct.	6.0	3.4	7.4	2.8
	Total Precipitation			
	mm			
Apr.	27.7	-15.3	35.6	-12.7
May	75.2	-35.0	81.0	-61.7
June	95.5	-43.4	94.5	-22.0
July	93.5	-65.2	79.0	-71.1
Aug.	68.8	29.2	65.0	13.3
Sept.	57.2	-21.1	67.3	12.0
Oct.	46.2	62.3	50.8	172.6

[a]Sites were located near Logan Center (LC) and Valley City (VC), North Dakota.
[b]Data from the Logan Center NDAWN weather station, 1.3 km from the LC site.
[c]Data from the Fingal NDAWN weather station, 14.5 km from the VC site.

3.3.2. Experimental Design

Prior to the establishment of this cover crop study, a two-row malting barley N-rate study was completed prior to cover crop planting (Goettl et al., 2024). The N rate study consisted of five fertilizer N rates (0, 45, 90, 135, and 180 kg N ha^{-1}) and two, two-row barley cultivars (ND Genesis and AAC Synergy). Following the barley harvest, mixed species cover crops and no-cover crop treatments were established. The cover crop mixes included species such as radish

(*Raphanus sativus* L.), flax (*Linum usitatissimum* L.), faba bean (*Vicia faba* Roth), and cereal rye (*Secale cereale* L.). These species were chosen based on their common or potential usage in North Dakota and their tolerance of late-summer and fall-weather conditions (Berti and Wick, n.d.; Northern Great Plains Research Laboratory, 2012).

The experiment was arranged as a randomized complete block design with a split-plot arrangement with each experimental unit measuring 2.4-m wide by 12.2-m long. Cover crop was the whole-plot treatment and N rate of the barley crop the sub-plot treatment, with five replicates at each location (n=50).

3.3.3. Barley Management

The two-row malting barley N rate experiments were planted on April 5, 2021 at VC and April 6, 2021 at LC. Barley was sown in 19-cm rows at the seeding rate of 3.08 million seeds ha^{-1} using a John Deere 1890 No-Till Air Drill (Deere and Co.). In-furrow fertilizer (12% N, 40% P_2O_5, 4% Zn) was used on both of the 2021 sites at the rate of 84 kg ha^{-1} at VC and 112 kg ha^{-1} at LC (Franzen and Goos, 2019). At the LC site, 1.1 L ha^{-1} of MCPA Ester, 1.4 L ha^{-1} of WideMatch (Corteva Agriscience), and 1.1 L ha^{-1} of Axial Bold (Syngenta Crop Protection) were applied post emergence to control weeds with 1.0 L ha^{-1} Caramba Fungicide (BASF Corporation) applied at heading to control disease. At the VC site 1.4 L ha^{-1} Cleansweep (Nufarm Inc.) herbicide and 146 mL ha^{-1} Tilt (Syngenta Crop Protection) fungicide was applied post emergence. Herbicide and fungicide applications were completed by the cooperating farmers.

At the time of barley planting, N fertilizer was hand-broadcast applied to the specific treatments. To limit the amount of N lost to volatilization, SUPERU (46% N) was used as the fertilizer N source. SUPERU is a urea-based fertilizer treated with dicyandiamide and N-(n-butyl) thiophosphoric triamide, which are a nitrification inhibitor and urease inhibitor, respectively (Koch Agronomic Services LLC, 2019). Additionally, 112 kg ha^{-1} of pelletized gypsum (calcium sulfate, 20% S) was broadcast applied at the time of N application to ensure that S deficiency did not confound N response.

Grain was direct harvested using an ALMACO plot combine on August 5, 2021 at VC and August 11, 2021 at LC. To limit edge interaction from N movement among the treatments, only the center 1.52 m of each experimental unit was harvested for data collection purposes. Following plot harvest, the remainder of the standing grain was harvested by the cooperating farmers. Care was taken to ensure the cutting height of the cooperator's combine was lower than the plot combine height, this facilitated all straw to be picked up, chopped by the combine and evenly distributed across the experimental units. More information regarding data collection, analyses, and results for the malting barley N rate study can be found in Goettl et al., (2024).

3.3.4. Cover Crop Management

Following the harvest of the barley crop, a mixed species cover crop consisting of 2.2 kg ha^{-1} forage radish, 2.2 kg ha^{-1} brown flax, and 33.6 kg ha^{-1} faba bean was no-till drilled in 19-cm rows at each site on August 19, 2021. To assist with nodulation of the faba bean, N-Charge Pea/Vetch/Lentil inoculant (Verdesian Life Sciences) was mixed with the seed prior to planting. N-Charge is a dry, peat-based inoculant containing 1% by weight *Rhizobium leguminosarum biovar viceae* and was applied at the recommended rate of 70.8 g per 22.7 kg of seed (Verdesian Life Sciences, 2015). At both sites, volunteer barley was allowed to grow with the cover crops. From the plant counts at both sites and a seed weight of 29,956 seeds kg^{-1} (13,600 seeds lb^{-1}) (Smith, 2021) the seeding rate of the volunteer barley was estimated to be 78.4 kg ha^{-1} at the LC site and 51.2 kg ha^{-1} at VC. To facilitate planting, all plots were sown with a cover crop and on

September 19, 2021, 2.3 L ha^{-1} Roundup PowerMAX (Bayer CropScience) was applied to terminate the emerged cover crops on the no-cover crop treatments.

3.3.5. Data Collection and Analysis

Above ground cover crop biomass was collected on October 18, 2021 at LC and October 19, 2021 at VC, timed prior to the first anticipated killing frost. Biomass samples were taken from a 0.2-m^2 area in each experimental unit. Cover crops were then separated by species for further analysis. After the samples were dried at 60 ℃ for 48 h, dry matter weight was determined. Samples were then ground and analyzed for total N content using an XDS Rapid Content Analyzer (FOSS).

Soil to be tested for NO_3-N was sampled to a depth of 60 cm in each experimental unit following barley harvest, prior to cover crop planting. Additionally, soil samples for NO_3-N analysis were taken following cover crop biomass harvest on October 18, 2021. All soil samples were analyzed by the NDSU Soil Testing Laboratory using the water extractant method (Nathan and Gelderman, 2012; Franzen, 2018).

Soil aggregate stability and aggregate size distribution was measured in the spring of 2022. Sub-samples were randomly collected from a depth of 0-5 cm and combined to make one sample for each of the main plots. The samples were air-dried and sieved to collect the ≤8-mm soil aggregates. Wet aggregate stability and aggregate size distribution was determined using the procedure outlined by Six et al. (1998). Samples of air-dried soil aggregates weighting 50 g were placed on a 2000 μm sieve and submerged in water for 5 min followed by 2 min of up-and-down agitation consisting of 50 repeated 3-cm cycles. Soil and water which passed through the sieve were transferred to progressively smaller sieves (250 μm and 53 μm) and the agitation and collection process repeated. Aggregates remaining on their respective sieves were transferred to a container and dried at 55 °C and the total aggregate mass was determined. To determine the amount of sand and coarse materials (non-aggregate material) a sub-sample from each aggregate size fraction was dispersed with sodium hexametaphosphate and sieved to determine sand content. The amount of sand was then subtracted from the total aggregate mass within each fraction.

Data analysis was performed using JMP Pro 17 (SAS Institute). Analysis of variance (ANOVA) was carried out as a randomized complete block design for residual NO_3-N prior to cover crop planting, cover crop biomass, and aggregate stability data. Soil NO_3-N following cover crops, and net change in soil NO_3-N was analyzed as randomized complete block design with a split-plot arraignment. In all analyses, replication (block) was considered a random effect. Location, N-rate, cover crop treatment, and cover crop species were considered fixed effects, where applicable. Homogeneity of the variance was affirmed if the ratio of the largest variance to the smallest is 10 or less (C. Doetkott, personal communication, Dec. 18, 2023). Mean separation was performed using Tukey's Procedure. Data in this study was considered statistically significant at $p \leq .05$.

3.4. Results and Discussion

3.4.1. Cover Crop Biomass Productivity

At both experimental locations, the volunteer barley produced the greatest above-ground dry biomass at the end of the season of all the cover crop species, 1530 kg ha^{-1} and 3210 kg ha^{-1} at VC and LC, respectively (Table 3.4). Although the barley produced greater dry biomass at LC compared to VC, radish and faba bean had greater dry biomass production at the VC site. Most notably the forage radish produced 575 kg ha^{-1} of biomass at VC compared to 6 kg ha^{-1} at LC. The limited growth of the radish, flax, and faba bean at LC may be attributed to the greater population and competitiveness of volunteer barley at LC; 2.3 million volunteer barley plants ha^{-1} emerged at the LC site compared to 1.53 million plants ha^{-1} at VC.

The competition from the greater population of volunteer barley at the LC site may have suppressed the growth of the other cover crop species (White and Barbercheck, 2017). The estimated volunteer barley seeding rate was 78.4 kg seed ha^{-1} at the LC site and 51.2 kg seed ha^{-1} at VC. Recommended broadcast seeding rate for a barley-only cover crop stand is 67-100 kg pure live seed ha^{-1} (Smith, 2021), which has shown promise in suppressing weeds (Smith, 2021). Given the high seeding rate at LC, the barley also suppressed the growth of the flax, radish, and faba bean compared to the volunteer stand at VC.

It should be noted that acceptable harvest loss for barley is 3% of total yield (Hofman and Kucera, 1978), which for these sites is an average of 48.6 kg ha^{-1}. Due to harvest equipment constraints, harvest losses in these experiments were higher than will likely be experienced at a production scale. More favorable performance of the flax, radish, and faba bean could likely be expected in similar climatic conditions with lower volunteer barley pressure.

A general increasing trend in cover crop biomass production with increased barley N fertilizer rate was noted, related mostly to the barley constituent of the cover crop mix (Table 3.4). Expectedly, this also means the amount of N immobilized in the cover crop biomass is correlated to the increase in fertilizer rate which resulted in greater residual N following barley harvest (Table 3.5). As illustrated in Figure 3.1, a significant relationship exists between residual NO_3-N following barley harvest and total cover crop biomass (r^2=0.42).

Table 3.4. Above ground biomass production and N content means and standard deviation of the mixed species cover crop following barley at two locations in eastern North Dakota.

Effect	**Variable**	**Barley Biomass**	**Radish Biomass**	**Faba Bean Biomass**	**Flax Biomass**	**Total Biomass**	**Biomass N Content**
		kg ha^{-1}					
Location[a] (Loc)	LC	3210±950 a	6±8 b	5±8 b	3±3	3230±942 a	63±33
	VC	1530±682 b	575±668 a	34±40 a	4±8	2140±871 b	62±35
	p-value	<.001	<.001	.001	.420	<.001	.856
N Fertilizer Rate (N) (kg N ha^{-1})	180	2660±1250 a	605±973	11±15	1±2	3270±819 a	95±34 a
	135	2910±1150 a	240±389	20±27	3±5	3180±1110 a	82±32 ab
	90	2590±1200 a	260±510	33±61	5±7	2880±925 a	62±22 bc
	45	2290±1050 a	167±269	16±21	3±3	2480±928 ab	48±14 cd
	0	1410±782 b	179±254	17±16	6±9	1610±603 b	26±5 c
	p-value	.001	.051	.465	.491	<.001	<.001
Loc x N	LC 180	3720±650	4±6 b	0±0	0±0	3720±652	91±35
	LC 135	3670±1164	4±6 b	12±14	3±3	3690±1149	85±35
	LC 90	3520±724	5±3 b	3±4	5±0	3540±728	66±16
	LC 45	3060±788	11±16 b	1±2	4±4	3080±778	50±12
	LC 0	2090±400	6±6 b	8±7	3±3	2110±397	24±2
	VC 180	1600±558	1210±1110 a	23±14	3±3	2830±767	100±35
	VC 135	2160±447	477±448 ab	28±36	3±6	2670±903	79±32
	VC 90	1650±717	515±651 ab	64±77	5±11	2230±577	58±29
	VC 45	1520±625	324±318 b	32±20	2±3	1880±656	46±16
	VC 0	731±239	353±264 b	26±18	9±12	1120±214	28±7
	p-value	.699	.048	.356	.619	.965	.897

[a]Sites were located near Logan Center (LC) or Valley City (VC), North Dakota.

Note: Means with the same letter within each effect are not significantly different at p=.05.

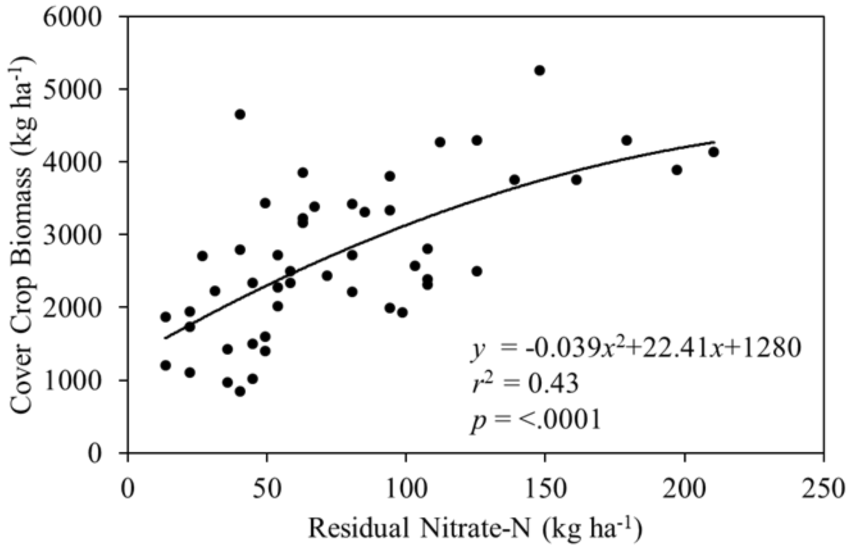

Figure 3.1. Above-ground biomass of the barley, radish, flax, and faba bean cover crop increased quadratically with increasing residual NO_3-N measured to a depth of 60 cm at the time of cover crop planting on August 19, 2021 at two eastern North Dakota sites.

3.4.2. Soil Nitrate Levels Following Barley Harvest

Following barley harvest, residual soil NO_3-N ranged from 13 to 287 kg N ha^{-1} at LC and 13 to 130 kg N ha^{-1} at VC. Higher malting barley N-rates led to greater residual NO_3-N following harvest (Table 3.5). Prior to planting the malting barley, soil NO_3-N levels at VC and LC averaged 49 kg N ha^{-1} and 60 kg N ha^{-1}, respectively. Barley productivity was lower at the VC site also, leading to less potential N uptake by the crop. Lower levels of NO_3-N at the VC site compared to LC may partially be attributed to the sandy soil texture at VC coupled with above average September and October rainfall, factors which increase the potential for NO_3^- leaching.

Table 3.5 Mean soil NO_3-N concentration and standard deviation following two-row malting barley harvest at two eastern-North Dakota locations. Five fertilizer N rates were applied to the barley at the time of planting, ranging from 0-180 kg N ha^{-1}.

Effect	**Variable**	**NO_3-N**
		kg N ha^{-1}
Location[a] (Loc)	LC	104±62 a
	VC	56±31 b
	p-value	.006
N Fertilizer Rate (N) (kg ha^{-1})	180	116±62 a
	135	112±53 a
	90	75±46 b
	45	65±42 bc
	0	36±14 c
	p-value	<.001
Loc x N	LC 180	159±62 a
	LC 135	144±48 ab
	LC 90	98±49 bc
	LC 45	84±49 cd
	LC 0	40±15 d
	VC 180	78±30 bcd
	VC 135	80±36 bcd
	VC 90	45±21 cd
	VC 45	45±22 cd
	VC 0	31±11 cd
	p-value	.005

[a]Sites were located near Logan Center (LC) or Valley City (VC), North Dakota.
Note: Means with the same letter within each effect are not significantly different at p=.05.

3.4.3. Impact of Cover Crops on Soil Nitrate-Nitrogen

Planting a cover crop following malting barley decreased the concentration of soil NO_3-N at the end of the growing season (Table 3.6). Although increased N fertilizer rate of the barley crop correlated to increased NO_3-N levels prior to cover crop planting (Table 3.6), these differences did not carry through to the end of the growing season on either the cover cropped or non-cover cropped treatments. Overall, LC had higher NO_3-N levels both at the time of barley harvest and at the end of the growing season compared to the VC site.

Table 3.6. Mean soil NO_3-N content and standard deviation sampled to a depth of 60 cm on October 18, 2021 following a mixed cover crop and no cover crop treatments seeded following malting barley at two eastern North Dakota locations.

Effect	Variable	NO_3-N
		kg N ha^{-1}
Location[a] (Loc)	LC	40±42 a
	VC	14±5 b
	p-value	.001
Cover Crop (CC)	No Cover Crop	40±42 a
	Cover Crop	13±5 b
	p-value	<.001
N Fertilizer Rate (N)	*p*-value	0.1431
Loc x CC	LC No Cover Crop	66±47 a
	LC Cover Crop	15±6 b
	VC No Cover Crop	15±5 b
	VC Cover Crop	12±5 b
	p-value	<.001
Loc x N	*p*-value	.334
CC x N	*p*-value	.462
Loc x CC x N	*p*-value	.392

[a]Sites were located near Logan Center (LC) or Valley City (VC), North Dakota.
Note: Means with the same letter within each effect are not significantly different at p=.05.

In LC, the no cover crop treatment retained an average of 66 kg N ha^{-1} compared to 15 kg N ha^{-1} in the cover cropped treatment at the time of cover crop termination in the fall, which is a 77% reduction in residual N in the soil, most likely taken up by the cover crop. When considering the interaction between location and cover crop treatment (Table 3.6) on residual fall NO_3-N, there were no differences noted with the presence of cover crops at the VC site. Based on biomass accumulation and biomass N content, the cover crop did take up and immobilize N. The amount of N lost in the no cover crop treatment to either leaching, microbial immobilization, or volatilization, was statistically equal to the amount retained in the cover crops (Table 3.4, Table 3.6, Figure 3.2).

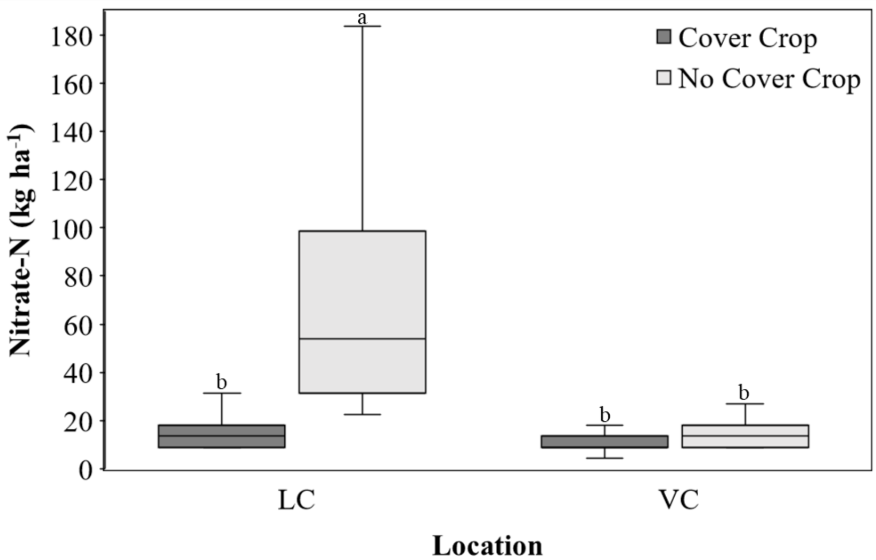

Figure 3.2. NO_3-N at the time of cover crop termination in October, 2021 at two sites in eastern North Dakota. The mixed species cover crop was sown following harvest of two-row barley. Cover crops accumulated 1530 kg ha^{-1} and 3210 kg ha^{-1} dry biomass at VC and LC, respectively.

As noted in several instances, the VC site had lower soil NO_3-N both before and after the cover crop. To compare the sites with these differences in mind, the change in NO_3-N within each experimental unit was considered and calculated as the difference between residual NO_3-N following barley harvest and end of season NO_3-N (Table 3.7). Both the cover crop and non-cover crop treatments resulted in a decrease in soil NO_3-N; however, the decrease in NO_3-N was significantly greater in the cover crop treatment, at 67 kg N ha^{-1}. Averaged between both sites, the amount N immobilized in the cover crop biomass was 63 kg ha^{-1} (Table 3.4), meaning the majority of the N removed from the soil profile was accumulated by the cover crops as opposed to 39 kg N ha^{-1} lost from the profile during the same time period, as was the case with the no-cover crop treatment.

Table 3.7. Change in soil NO_3-N and standard deviation in mixed cover crop and no cover crop treatments following malting barley at two eastern North Dakota locations. Samples were collected at the time of cover crop planting on August 19, 2021 and again at the end of the growing season on October 16, 2021. Samples were taken to a depth of 60 cm.

Effect	**Variable**	**Reduction in NO_3-N**	
		kg N ha^{-1}	%[a]
Location (Loc)	*p*-value	.079	.082
Cover Crop (CC)	Cover Crop	-67±51 a	76±19 b
	No Cover Crop	-39±54 b	48±40 a
	p-value	.004	<.001
Fertilizer N Rate (N) (kg ha^{-1})	180	-84±59 a	72±26 a
	135	-77±52 ab	67±28 ab
	9	-49±45 abc	63±32 ab
	45	-45±44 bc	62±31 ab
	0	-12±40 c	46±47 b
	p-value	<.001	.033
Loc x CC	LC No Cover Crop	-38±7 2a	30±47 b
	LC Cover Crop	-89±58 b	80±12 a
	VC No Cover Crop	-40±31 a	65±21 a
	VC Cover Crop	-44±29 a	71±23 a
	p-value	.013	<.001
Loc x N	*p*-value	.350	.931
CC x N	*p*-value	.813	.952
Loc x CC x N	*p*-value	.527	.898

[a]Percent reduction in NO_3-N is calculated as NO_3-N prior to cover crop planting minus NO_3-N at the end of the growing season divided by NO_3-N prior to cover crop planting.
Note: Means with the same letter within each effect are not significantly different at p=.05.

Regardless of the presence of cover crops, the change in soil NO_3-N was greater with increasing fertilizer N rate on the previous barley crop, which is not unexpected since more N was in the system and available to loss or uptake (Table 3.5). Fortunately, in most cases if proper fertility recommendations are followed for malting barley, such as described in Franzen (2023) and Goettl et al. (2024), the excessive N applications, which lead to increased residual NO_3-N, could be limited. Barley N treatments, which were within economic application rates from 89-190 kg TKAN ha^{-1} (Goettl et al., 2024), resulted in residual soil NO_3-N ranging from 36 to 80 kg

N ha^{-1} at the time of barley harvest (TKAN, total known available nitrogen is calculated as the sum of pre-plant soil NO_3-N, crop N credits, and fertilizer applied (Franzen, 2018, 2023)). Based on the trend noted in Figure 3.1, approximately 2000-2500 kg ha^{-1} of cover crop biomass was produced from the residual N from the recommended fertility levels for malting barley.

Although not all residual N in the soil can be retained in a cover crop and protected from leaching, the presence of a cover crop does increase the total amount of N residing in the field at the end of the growing season, in an organic form (Table 3.7). The sum of soil NO_3-N and N retained in cover crop biomass end of the growing season is significantly greater the cover crop treatments compared to the non-cover crop treatments, where only soil NO_3-N is retained. This trend also carries through to the N-rate treatments as well; although no statistical differences were noted in end-of-season residual NO_3-N related to N-rate of the barley crop (Table 3.6), a difference is noted when biomass N is taken into consideration (Table 3.7).

Table 3.8. Soil NO_3-N content sampled to a depth of 60 cm plus N in above-ground cover crop biomass collected October 18, 2021 from mixed cover crop and no cover crop treatments seeded following malting barley at two eastern North Dakota locations.

Effect	**Variable**	**Soil NO_3-N + Biomass N**
		kg N ha^{-1}
Location[a] (Loc)	LC	72±41 a
	VC	45±39 b
	p-value	.004
Cover Crop (CC)	Cover Crop	76±35 a
	No Cover Crop	40±42 b
	p-value	<.001
Fertilizer N Rate (N) (kg ha^{-1})	180	82±53 a
	135	76±50 ab
	90	54±32 bc
	45	44±22 c
	0	37±33 c
	p-value	<.001
Loc x CC	LC No Cover Crop	66±47 a
	LC Cover Crop	78±35 a
	VC No Cover Crop	15±5 b
	VC Cover Crop	74±5 a
	p-value	<.001
Loc x N	*p*-value	.658
CC x N	CC 180	112±36 a
	CC 135	97±32 ab
	CC 90	75±23 abc
	CC 45	58±12 bcd
	CC 0	39±4 cd
	NC 180	49±51 cd
	NC 135	55±57 cd
	NC 9	33±24 d
	NC 4	29±20 d
	NC 0	35±48 cd
	p-value	.049
Loc x CC x N	*p*-value	.453

[a]Sites were located near Logan Center (LC) and Valley City (VC), North Dakota.
Note: Means with the same letter within each effect are not significantly different at *p*=.05.

3.4.4. Aggregate Stability

Biological factors play a significant role in the stability of soil aggregates. Previous research shows aggregation in cover-cropped soils improve even after a short period or one growing season compared to bare soils (Hermawan and Bomke, 1997; Blanco-Canqui et al., 2011; Algayer et al., 2014; Finney et al., 2017). However, this study did not result in any differences in any aggregate size fraction (Table 3.9).

Table 3.9. Percent water stable aggregates sampled in the spring of 2022 following cover crop and no-cover crop treatments at two locations in eastern North Dakota.

		Soil Aggregate Size Fractions			
Effect	**Variable**	**2000 µm**	**250 µm**	**53 µm**	**>53 µm**
		%			
Location[a] (Loc)	LC	5±3	34±2 a	25±2 a	64±1 a
	VC	5±2	14±4 b	8±3 b	27±8 b
	p-value	.670	<.001	<.001	<.001
Cover Crop (CC)	No Cover Crop	5±2	25±11	17±9	46±20
	Cover Crop	6±3	23±10	16±9	44±19
	p-value	.314	.206	.681	.531
Loc x CC	*p*-value	.946	.779	.890	.928

[a]Sites were located near Logan Center (LC) or Valley City (VC), North Dakota
Note: Means with the same letter within the same effect and column are not significantly different at the p=.05 probability level.

Percent of water stable aggregates (WSA) greater than 53 µm in soil varies due to many physical, chemical, and biological factors (Tisdall and Oades, 1982; Bronick and Lal, 2005) and generally the greater percentage of WSA is more favorable. Based on the properties of each site, Soil Quality Institute (1999) considered 74-77% at LC and 65-75% at VC as suitable %WSA. According to another source, WSA >35% at LC and >45% at VC are considered “High” (Moebius-Clune et al., 2016). Although there is a disagreement in ideal levels of WSA, the percentages at these sites vary greatly compared to each other. The LC site trends toward satisfactory levels, while VC is far from favorable by both scoring ranges. Due to the no-till management of these sites, it can be speculated the percent WSA is higher than what would be measured if the soil was disturbed by yearly tillage (Blanco-Canqui and Ruis, 2018). Further, it is likely aggregation decreased over the winter as also noted in Hermawan and Bomke, (1997), Perfect et al., (1990), and Chan et al., (1994). Seasonal freeze-thaw cycles also are particularly detrimental to aggregates at these sites where to 2:1 smectitic clays are present (Franzen and Bu, 2018; D. Franzen, personal communication, Feb. 2, 2022). Coupling these factors with the coarse texture, low OM, and severely dry conditions at VC, changes in WSA could be expected in future sampling years or timings.

3.5. Management Implications

Cover crops following barley have the potential to take up residual NO_3-N, provide other environmental benefits (Sarrantonio and Gallandt, 2003; Blanco-Canqui et al., 2013), and fit into the rotation with minimal impacts to the cropping system. However, there is a cost associated with planting and managing the cover crop. The seed cost of the 2.2 kg ha^{-1} forage radish, 2.2 kg ha^{-1} brown flax, and 33.6 kg ha^{-1} faba bean cover crop mix used in this study is approximately \$124 ha^{-1}, with faba bean making up the majority of the expense at \$107 ha^{-1} (Agassiz Seed, Fargo, ND, personal communication, March 5, 2024). Coupling the seed with \$41 ha^{-1} no-till drilling costs (NDSU-Extension, 2020) total cost for the cover crop is \$165 ha^{-1}, which may be cost prohibitive to farmers, especially since other common management practices following barley harvest, such as tillage or herbicide control of weeds, are substantially less expensive. For example, depending on intensity of tillage from vertical-tillage to chisel plow and disking, tillage costs range from \$26-\$55 ha^{-1} (NDSU-Extension, 2020). To control weeds, an application of glyphosate and 2,4-D herbicide, with spray application costs \$43 ha^{-1} (NDSU-Extension, 2020; Ikley, 2023).

Since the environmental and rotational benefits of cover crops are difficult to quantify economically, high costs of implementation are difficult for producers justify (Schnitkey et al., 2023). Ensuring cover cropping practices are economically feasible will increase the likelihood of adoption. With limited biomass production of the fava bean in this study (Table 3.4), not including it in the cover crop mix would reduce the implementation cost of the cover crop to \$58 ha^{-1}. Utilizing the volunteer barley is also essential to reducing the costs; if oat or barley seed was purchased to plant in place of the volunteer, this would add an additional cost of \$82 ha^{-1} to seed at 50 kg ha^{-1} (Agassiz Seed, Fargo, ND, personal communication, March 5, 2024). Based on estimated acceptable harvest loss of 3% (Hofman and Kucera, 1978), 49 kg ha^{-1} of volunteer barley seed can be reasonably expected. Reducing the costs to cover crop implementation through reduced seeds costs helps to remove one of the barriers to cover crop adoption.

3.6. Conclusion

Establishing cover crops following the harvest of two-row barley provides an opportunity for farmers in the northern Great Plains to integrate cover crops into their cropping systems. By taking advantage of the volunteer barley, the cost of the cover crop can be greatly reduced while still providing the soil health and erosion-prevention outcomes associated with cover cropping practices. The cover crop used in place of a fallow period can also be used as a tool to manage residual soil NO_3-N which is at risk for leaching and loss. The growing, N-demanding, crop immobilizes N preventing its loss from the system in leaching-prone soils, such as the VC site, retaining a more N at the end of the growing season as compared to bare fallow. Although this project did not evaluate the fate of the N in the cover crop biomass, it demonstrated the efficacy for cover crop establishment following malting barley and its ability to be used as an N-capturing tool.

3.7. References

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4. THE IMPACTS OF COVER CROPS ON SUBSEQUENT CROP YIELD AND NITROGEN POOLS IN NORTH DAKOTA CROPPING SYSTEMS

4.1. Abstract

Cover crops have proven effective in reducing wind and water erosion, improving soil health, and capturing excess N in the fall to prevent leaching. Although the benefits of cover crops to soil health are widely reported, their impact on the yield of the following crops is not clear. The purpose of this study was to determine the impact cover crops have on the yield of following corn and wheat crops along with quantifying nitrogen pools in the soil. Following barley, cover crops were no-till seeded at three eastern North Dakota sites in 2021 and 2022. Prior to frost termination, above-ground cover crop biomass ranged from 740 to 2,900 kg ha^{-1} across locations. The following spring, corn grain was planted into cover crop and no-cover crop treatments and fertilized with five N rates (0 to 180 kg N ha^{-1}) in a randomized complete block design with a split-plot arrangement. The following year, wheat was planted on these sites and fertilized with the same N rates. After corn and wheat harvest, grain yield was determined and soil samples were taken to a depth of 60 cm and analyzed for NO_3-N, NH_4-H, and non-exchangeable NH_4-N. The cover crop had no significant impact on corn or wheat yield, however, it did appear the cover crop had an impact on the wheat yield response to N. The total known available N (TKAN, sum of preplant soil NO_3-N, N credits and fertilizer N) needed to reach maximum yield in the no cover crop treatments was 263 kg TKAN ha^{-1} while wheat grown two seasons following the cover crop was 182 kg TKAN ha^{-1}, indicating a potential second-year credit from cover crops may be attainable.

4.2. Introduction

Cover crops, when planted during otherwise fallow periods take up residual soil N, primarily in the NO_3 form (Schulte et al., 2009), and reduce potential losses from the system through leaching or denitrification (Tonitto et al., 2006; Gabriel et al., 2014; Finney et al., 2016; Lee et al., 2016). In addition to the environmental benefits of reducing N leaching, there may be productivity and economic benefits to retaining N in cover crop biomass, if it becomes available to subsequent cash crops (Hughes and Langemeier, 2020). However, for these benefits to be realized, the N sequestered in cover crop biomass must become plant available in the following years. In addition to C:N ratio, time of cover crop termination, quantity of biomass produced, soil characteristics, and climatic conditions also play a role in mineralization of cover crop-sequestered N (USDA-Natural Resources Conservation Service, 2010; Ruark and Franzen, 2020). However, previous research in Wisconsin, North Dakota, and Iowa with corn planted following both legume and non-legume cover crops resulted in no consistent corn yield increase, illustrating a lack of N contribution from the cover crop (Pantoja et al., 2015; Ruark et al., 2018; Andersen et al., 2020; Leiva, 2020; Ruark and Franzen, 2020). With N in cover crop biomass not becoming available the subsequent year, several potential processes may be occurring including NH_3 volatilization from the biomass in no-till systems (Sarrantonio and Scott, 1988; Janzen and McGinn, 1991; Vaisman et al., 2011), microbial immobilization of N (Muramoto et al., 2011) and tie-up of NH_4 in clay minerals (Franzen and Bu, 2018; Leiva, 2020).

As the result of mineralization, inorganic, plant available soil N is present primarily in two forms: NO_3 and NH_4. NO_3 resides in the soil solution and does not interact with the negatively charged clay and organic matter (OM) particles present in soils, thus making it susceptible to leaching. NH_4, however, does have the capacity to be adsorbed to exchange sites within CEC-dominated soils or reside in the soil solution. This NH_4, which is readily plant available, or may become available through cation exchange, is considered exchangeable NH_4.

Non-exchangeable NH_4, also referred to as fixed NH_4, cannot be extracted from the soil using standard methods due to its fixation within 2:1 clay minerals (Nommik and Vahtras, 1982; Mulvaney, 2018). Soils containing 2:1 expanding clay minerals (smectite and vermiculite) have the capacity not only to retain NH_4 through CEC, but in large concentrations of NH_4 in drying conditions these cations cause interlayer spacing to decrease fixing the ion within the clay mineral structure (Steffens and Sparks, 1997; Franzen and Bu, 2018). As the concentration of NH_4 is depleted in the non-fixed forms, the clay mineral will begin slowly releasing these fixed ions (Steffens and Sparks, 1997; Nommik and Vahtras, 1982). Levels of non-exchangeable NH_4 in the soils vary greatly depending on clay mineralogy, texture, and CEC. Nunes et al., (2019) reported non-exchangeable NH_4-N levels ranging from 15.1 mg N kg^{-1} to 511.6 mg N kg^{-1} (135-4584 kg N ha^{-1}) across differing analysis methods and soil types. A sample from a Fargo Series soil (Soil Survey Staff, 2023), containing primarily montmorillonite, illite, and kaolinite, was found to have an average 2332 kg N ha^{-1} in the non-exchangeable NH_4-N form (Nunes et al., 2019).

This fixation and release of NH_4 may have practical implications on crop production and management practices, especially in areas with 2:1 expanding clay minerals, such as North Dakota (Franzen and Bu, 2018). Following fall cover crops, the processes of ammonification and mineralization of N in cover crop biomass would expectedly occur in late spring or early summer, when soil temperatures are 20-30 °C (Davidson and Janssens, 2006) and the soil is well aerated. In crop production systems as the cover crop biomass is decomposed and N mineralized, additional NH_4 is typically being applied to the soil as fertilizer, increasing the total level of NH_4

in the soil. Given field conditions in the spring are typically going through drying processes from saturated conditions experienced during snowmelt and spring rains, two conditions favoring NH_4 fixation are presented: increasing levels of NH_4 (Steffens and Sparks, 1997; Nommik and Vahtras, 1982) and drying conditions (Nommik and Vahtras, 1982). Although the process of fixation can happen rapidly (Steffens and Sparks, 1997) the release of non-exchangeable NH_4 is more delayed and may contribute to plant available N during the growing season (Franzen, 2022a).

Studies relating the use of cover crops to following crop yield have had highly variable results. Some studies show the use of cover crops can improve the following crop yield (Andraski and Bundy, 2005; Reinbott et al., 2004; Muramoto et al., 2011; Blanco-Canqui et al., 2012; Snapp and Surapur, 2018), while other studies show the opposite, mixed, or neutral effects (Kuo and Jellum, 2000; Kuo et al., 2001; Fageria et al., 2005; O'Reilly et al., 2012; Berti et al., 2017b; Ruark et al., 2018; Ghimire et al., 2019; Andersen et al., 2020; Leiva, 2020; Franzen et al., 2023). The impact of cover crops on yield of the following crop is not clear and N from cover crop biomass does not become readily available the following growing season (Ruark et al., 2018; Leiva, 2020; Ruark and Franzen, 2020). The purpose of this study was to determine the impact cover crops have on soil NO_3-N, NH_4-H, and non-exchangeable NH_4-N and the yield of the following and subsequent crops or wheat and corn.

4.3. Methods and Materials

4.3.1. Site Description

This experiment was conducted from 2021 to 2023 at three non-irrigated locations in Barnes, Grand Forks, and Cass Counties in North Dakota, near Valley City (46.880486N, 97.913760W), Logan Center (47.791001N, 74 97.775661W), and Gardner (47.175694N, 96.920118W) (Table 4.1). The sites were all managed under no-tillage practices and were planted with a cover crop following small grains the year prior to the establishment of this project. Gardner and VC had been under no-till management for >6 years at the inception of this study, LC <6 years.

Table 4.1. Soil properties in the top 15 cm at three sites in eastern North Dakota.

			Size Fractions			**Primary Clay Fractions**[a]	
Site[b]	**Year Established**	**Soil Type**	**Sand**	**Silt**	**Clay**	**Smectite**	**Illite**
Gardner	2023	Fargo[b]	15	41	44	19	5.2
LC	2022	Barnes[c]	39	34	26	5	5.3
VC	2022	Barnes	78	11	11	1	3.6

[a]Semi-quantitative analysis conducted by Activation Laboratories Ltd. (Ancaster, Ontario) using x-ray diffraction Analysis code 9-Mineral Identification (Rietveld) + Clay Speciation.
[b]Sites were located near Gardner, Logan Center (LC), and Valley City (VC), North Dakota.
[c]Fine, smectitic, frigid Typic Epiaquerts (Soil Survey Staff, 2023)
[d]Fine-loamy, mixed, superactive, frigid Calcic Hapludolls (Soil Survey Staff, 2023)

Weather varied across sites (Table 4.2) with the greatest impact to the project coming from low precipitation conditions at all sites. In general, precipitation was adequate for crop production, attaining only abnormally dry (D0) conditions during most of the corn and wheat growing seasons (National Drought Mitigation Center, 2024). The most severe drought conditions were experienced during cover crop establishment at LC and VC; from August-November, 2021 drought conditions ranged from abnormally dry (D0) to extreme drought (D3) (National Drought Mitigation Center, 2024).

Table 4.2. Mean air temperature and total precipitation at three sites in North Dakota based on 30-yr average and their departure from the average for each growing season, as reported by the North Dakota Agricultural Weather Network (NDAWN, 2024).

		Location[a]					
		LC[b]		**VC**[c]		**Gardner**[d]	
Project Crop Year	**Month**	**30-yr Average**	**Departure from 30-yr Average**	**30-yr Average**	**Departure from 30-yr Average**	**30-yr Average**	**Departure from 30-yr Average**
		Air Temperature					
		°C					
Cover Crop	July	20.2	2.4	20	2.5	21.5	-0.2
	Aug.	19.2	1	18.9	1.6	20.4	-0.7
	Sept.	14.1	2.7	13.9	2.7	15.6	-0.2
	Oct.	6	3.4	5.8	3.6	7.6	0.2
Corn	Apr.	4.2	-4.4	4.3	-4.3	6.1	-5.9
	May	12.1	-0.4	12	-0.3	13.5	3
	June	17.8	0.7	17.7	0.9	19.3	2.6
	July	20.2	0.6	20	0.9	21.5	-2.4
	Aug.	19.2	0.6	18.9	0.8	20.4	-0.2
	Sept.	14.1	1	13.9	1.3	15.6	2
	Oct.	6	1.6	5.8	1.7	7.6	0.2
Wheat	Apr.	4.2	-4.4	4.3	-4.4		
	May	12.1	3.9	12	4		
	June	17.8	3.4	17.7	3.3		
	July	20.2	-1.3	20	-1.1		
	Aug.	19.2	0.6	18.9	0.6		
		Total Precipitation					
		mm					
Cover Crop	July	93.5	-65.2	93.2	-69.1	88.1	-58.5
	Aug.	68.8	29.2	72.6	-28.4	70.1	-37.5
	Sept.	57.2	-21.1	58.4	-8.9	61.2	-43.3
	Oct.	46.2	62.3	46.7	63.1	49	-43.9
Corn	Apr.	27.7	102.2	27.4	112.2	34.5	-18.8
	May	75.2	58.1	77.2	86.3	72.4	-18.6
	June	95.5	-15.2	91.7	2	100.1	-60.6
	July	93.5	-39.1	93.2	-70	88.1	-61.4
	Aug.	68.8	-47	72.6	-35.9	70.1	-49.1
	Sept.	57.2	-40.6	58.4	-47.4	61.2	-18.1
	Oct.	46.2	-40.6	46.7	-40.8	49	11.9
Wheat	Apr.	27.7	29.1	27.4	1.7		
	May	75.2	-24.5	77.2	-34.7		
	June	95.5	-25.1	91.7	39.2		
	July	93.5	-79.5	93.2	-73.4		
	Aug.	68.8	-45.4	72.6	-19.6		

[a]Sites were located near Logan Center (LC), Valley City (VC), or Gardner North Dakota.
[b]Data from the Logan Center NDAWN weather station, 1.3 km from the LC site.
[c]Data from the Fingal NDAWN weather station, 14.5 km from the VC site.
[d]Data from the Hillsboro NDAWN weather station, 16.7 km from the Gardner site.

4.3.2. Experimental Design

Two of the locations in this study were a continuation of a two-row malting barley N rate experiment established in the spring of 2021 at VC and LC (Goettl et al., 2024). The barley study consisted of five N fertilizer rates ranging from 0 to 180 kg N ha^{-1} and two malting barley cultivars. An additional site, Gardner, was included in the analysis for this study. Wheat was grown at the Gardner site prior to cover crop establishment, fertilized with 90 kg N ha^{-1}. Following small grain harvest at each site, a mixed species cover crop was seeded. Following the cover crop, corn was planted the subsequent spring with wheat following the second year (Table 4.3).

Table 4.3. Key dates for crop harvest and planting from the year of project establishment to two crop years following at four sites in eastern-North Dakota.

	Study Year					
	Establishment		**Year 1**		**Year 2**	
Site[a]	**Small Grain Harvest**	**Cover Crop Seeding**	**Corn Planting**	**Corn Harvest**	**Wheat Planting**	**Wheat Harvest**
Gardner	Aug 23, 2022	Aug 25, 2022	May 24, 2023	Oct 17, 2023		
LC	Aug 11, 2021	Aug 19, 2021	May 28, 2022	Oct 5, 2022	May 19, 2023	Aug 30, 2023
VC	Aug 5, 2021	Aug 19, 2021	May 22, 2022	Oct 13, 2022	May 18, 2023	Aug 31, 2023

[a]Sites were located near Logan Center (LC), Valley City (VC) and Gardner, North Dakota.

The experiments were arranged as a randomized complete block design with a split-plot arrangement. Each experimental unit was 2.4-m wide by 12.2-m long at LC and VC and 3 m by 12.2 m at Gardner. Cover crop versus no cover crop was the main-plot treatment and N rate was the sub-plot treatment. Blocks were replicated three times at Gardner and five at VC and LC. Nitrogen fertilizer treatments applied to the subsequent corn and wheat crops were 0, 45, 90, 135, and 180 kg N ha^{-1}. The cover crop mix consisted of 2.2 kg ha^{-1} forage radish, 2.2 kg ha^{-1} brown flax, and 33.6 kg ha^{-1} faba bean at LC and VC; and 33.6 kg ha^{-1} oat, 2.2 kg ha^{-1} forage radish, and 2.2 kg ha^{-1} brown flax was planted at the Gardner site. These species were chosen based on their common usage in North Dakota and tolerance of late-summer and fall-weather conditions.

Cover crop biomass was collected in the fall prior to the first killing frost. Average above-ground biomass production at the Gardner, LC, and VC sites were 1259, 3226, and 2144 kg ha^{-1}, respectively. Although drought conditions were experienced during the cover crop growth period (Table 4.2) (National Drought Mitigation Center, 2024) the crop biomass production was representative of the productivity reported in similar cover crop planting systems in North Dakota (Berti et al., 2017a; Leiva, 2020).

4.3.3. Corn Management

At all of the three locations, corn was no-till planted in 76-cm rows on the dates indicated in Table 4.3. Seeding rates, corn cultivars, starter fertilizer, and pest management were determined and executed by the cooperating farmers. At Gardner, Pioneer 9188AM (Corteva Agricience) seed corn was planted at a population of 79,040 seeds ha^{-1} with 46 L ha^{-1} of 10-34-0 fertilizer banded at the time of planting in a 5-cm by 5-cm placement. Weeds were controlled with a post-emergence herbicide application of 0.93 L ha^{-1} atrazine, 1.5 L ha^{-1} Armezon PRO (BASF Corporation), and 1.6 L ha^{-1} Roundup PowerMAX (Bayer CropScience). LC was planted with Pioneer P7861AM at the rate of 79,040 seeds ha^{-1}, 89.6 kg ha^{-1} of 11-35-10-4s fertilizer was banded at the time of planting in a 5-cm by 5-cm placement. Roundup PowerMAX was applied post-emergence at the rate of 2.3 L ha^{-1}. Golden Harvest G48J92-GTA (Syngenta Group) corn was planted at VC at 69,160 seeds ha^{-1}, 28 L ha^{-1} of 9-18-9 fertilizer was applied 5-cm by 5-cm placement at the time of planting. Roundup PowerMAX was applied post-emergence at the rate of 2.3 L ha^{-1}. No cover crops were seeded following corn at any site.

4.3.4. Wheat Management

Wheat was no-till sown the year following corn in 19-cm rows at LC and VC, on the dates reported in Table 4.3. WestBred WB9590 (Bayer CropScience) was planted at LC at 3.2 M seeds ha^{-1} with 75 kg ha^{-1} 11-52-0 fertilizer applied in furrow. Weeds were controlled with 1 L ha^{-1} Huskie FX (Bayer CropScience) herbicide applied prior to flag leaf. VC was sown with MN-Torgy wheat (University of Minnesota) at 2.47 M seeds ha^{-1}. Prior to wheat jointing, 1.2 L ha^{-1} Cleansweep (Nufarm Americas Inc.) herbicide, 146 mL ha^{-1} Tilt (Syngenta Group) fungicide was applied.

4.3.5. Nitrogen Management

At the time of planting, N fertilizer was hand-broadcast applied to the specific 0, 45, 90, 135, and 180 kg N ha^{-1} treatments. To limit the amount of N lost to volatilization, SUPERU (46% N) was used as the fertilizer N source. SUPERU is a urea-based fertilizer treated with dicyandiamide and N-(n-butyl) thiophosphoric triamide, which are a nitrification inhibitor and urease inhibitor, respectively (Koch Agronomic Services LLC, 2019).

Corn and wheat response to N was determined using the total known available N (TKAN) approach (Franzen, 2023; Goettl et al., 2024) to determine maximum return to N (Sawyer and Nafziger, 2005). TKAN is calculated as the sum of preplant soil NO_3-N (N_S), prior crop N credits (N_{PC}), no-till N credits (N_{TC}), and amount of fertilizer N applied (N_{Fert}) (Eq 4.1)

$$TKAN = N_{PC} + N_{TC} + N_S + N_{Fert} \tag{4.1}$$

Tillage N credits reported in Franzen (2023) include a 44.8 kg N ha^{-1} credit assessed in systems under no-till management for >6 years; systems in transitional or intermittent no-till are penalized 22.4 kg N ha^{-1}. In this experiment, no prior crop N credits were assessed in any environment due to the previous crops of barley, wheat, or corn, in each respective environment.

Gardner and VC were credited 44.8 kg ha^{-1} long-term no-till N credit was each year, LC was penalized 22.4 kg ha^{-1} for being in the transitional no-till stage (Franzen, 2023).

4.3.6. Data Collection and Analysis

The corn was hand harvested by collecting the ears from one 12.2-m row within each experimental unit. The collected ears were transported to the lab where they were shelled and the grain yield, test weight, and moisture content were determined. Grain moisture and test weight were measured using a Dickey-John Model GAC500 XT grain analyzer (Dickey-John). Grain harvest weights were adjusted to the standard moisture content of 15.5% for yield calculations.

Wheat was direct-harvested using a plot combine (ALMACO). To limit edge interaction from N movement among the treatments, only the center 1.52 m of each experimental unit was harvested. Grain was collected in breathable cloth bags and transported to the laboratory for all post-harvest measurements and quality analyses. The harvested, field moist, grain samples were placed into convection driers at 60 °C for 12 h prior to processing. Samples were weighed and then cleaned using a Clipper Model-2B cleaner (A.T. Ferrell Co.) to improve grain for further analysis. Grain moisture and test weight were measured using a Dickey–John model GAC500 XT grain analyzer. Grain harvest weights were adjusted to the standard moisture content of 13.5% for yield calculations.

Soil samples were collected from the 0-60 cm depth in the spring prior to corn and wheat planting and fertilization, and again following crop harvest. These samples were immediately air dried before being analyzed for NO_3-N, NH_4-N, and non-exchangeable NH_4-N. NO_3-N and NH_4-N analyses were carried out by Agvise Laboratories (Northwood, North Dakota). Non-exchangeable NH_4-N was determined using a modified sodium tetraphenylboron method (Cox et al., 1996; J. Breker, personal communication, July 7, 2022).

The protocol used to determine non-exchangeable NH_4-N begins with a seven-day, room-temperature extraction. Into a 42x300 mm digestion tube, 2 g of air dried and ground soil mixed with an extractant solution of 4 mL 2.5M NaCl-0.01M EDTA and 2 mL $NaBPh_4$, mixed together immediately before adding to the soil. The extraction period lasted seven days at room temperature, with the samples being swirled once per day. Following the extraction, a quenching solution of 40 mL 0.5 M KCl and 10 mL 1.0 M $CuCl_2$ was added to the digestion tubes. The solution was boiled at 150 °C for 35 minutes using a Tecam DG-1 digestion block (Tecam Group). The samples were cooled and acidified with five drops of 36.5% HCl prior to steam distillation. Samples were distilled using a UDK 129 distillation unit (Velp Scientifica Srl), 60 mL of 33% w/v NaOH was added immediately prior to a 3.5 min distillation into 20 mL 4% H_3BO_3 indicator solution. The distillate was titrated using a 916 Ti-Touch auto titrator (Metrohm AG) with 0.01609N titrant. Percent concentration of NH_4-N in the soil was determined using Equation 4.2, taking into consideration the volume of titrant for the blank and sample, normality of titrant, milliequivalent weight of N × 100 (1.4007), and weight of soil sample. Extractable NH_4-N was subtracted to determine non-exchangeable NH_4-N.

$$\%\ NH_4\text{-N} = \frac{(\text{mL sample titrant} - \text{mL blank titrant}) \times \text{N of titrant} \times 1.4007}{\text{g soil}} \tag{4.2}$$

4.3.7. Statistical Analysis

Data analysis was performed using JMP Pro 17 (SAS Institute). Analysis of variance (ANOVA) was carried out as a randomized complete block design with a split-plot arrangement. Environment and replication (block) were analyzed as random effects and cover crop treatment and N rate as fixed effects for crop yield, quality, and soil N response. Non-exchangeable NH_4-N was also analyzed with environment as a fixed effect to draw conclusions on the impact of site-specific soil properties. Regression analysis was performed using JMP Pro 17 Nonlinear

Modeling. To compare yield response to TKAN relative yield was used; relative yield was calculated by dividing the yield of each experimental unit by the maximum yielding experimental unit at each site. This approach used in this study relies on the strong relationship between relative yield and TKAN (Franzen et al., 2021; Goettl et al., 2024) and recognizes the independence of actual crop yield and N rate (Vanotti and Bundy, 1994; Raun et al., 2011). Homogeneity of the variance was determined if the ratio of the largest variance to the smallest is 10 or less (C. Doetkott, personal communication, Dec. 18, 2023). Soil N concentrations measured in the fall of cover crop growth were not homogeneous and were therefore analyzed separately. Mean separation was performed using Student's t for comparing two means or Tukey's Procedure for comparing three or more. Data in this study was considered statistically significant at $p = .05$.

4.4. Results and Discussion

4.4.1. Corn Yield and Quality

Across the three environments, corn grain yield ranged from 1,040 to 13,260 kg ha^{-1}, averaging 9,420 kg ha^{-1}, 8,370 kg ha^{-1}, and 4,560 kg ha^{-1} at Gardner, LC, and VC, respectively. Based on county average corn grain yields of 10,100 kg ha^{-1}, 9,470 kg ha^{-1}, and 8,590 kg ha^{-1} (USDA National Agricultural Statistics Service, 2023) in the counties and crop years reflecting Gardner, LC, and VC, respectively, all sites except VC were near county levels; however, it must be noted the environment average yield also takes into consideration N-limited experimental units.

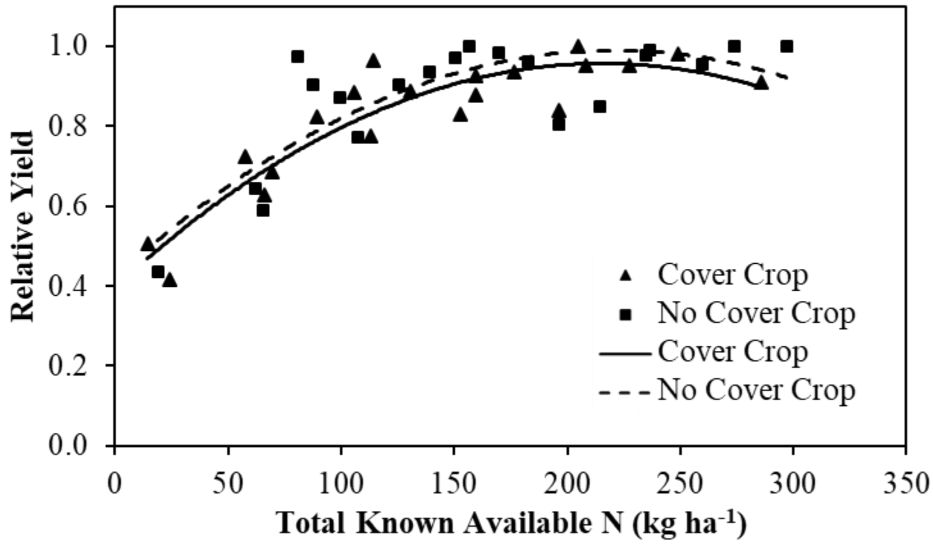
In the first cropping season following a late summer/fall cover crop, corn grain yield and test weight were not impacted by the presence of the cover crop (Table 4.4). Corn yield did show a significant response to N fertilizer rate, as expected.

Table 4.4. Mean and standard deviation corn grain yield and test weight planted following fall-seeded mixed species cover crops at three sites in eastern North Dakota.

Effect	Variable	Yield	Test Weight
		kg ha^{-1}	kg m^{-3}
Cover Crop (CC)	No Cover Crop	6880±2860	694±46
	Cover Crop	6370±2630	675±71
	p-value	.258	.167
N Rate (kg ha^{-1})	180	7350±2910 a	691±43
	135	7400±2860 a	693±41
	90	7000±2520 a	685±50
	45	6350±2430 ab	690±44
	0 kg	5020±2390 b	664±101
	p-value	.009	.321
CC x N Rate	*p*-value	.771	.379

Note: Means with the same letter within the same effect are not significantly different at the .05 probability level.

When TKAN is compared to relative corn yield (Figure 4.1), the maximum relative yield on the response curve for the no cover crop treatment is slightly greater compared to the cover cropped treatment, but not at a statistically significantly level. Maximum potential yield for the cover crop and no cover crop treatment is attained at 212 and 213 kg TKAN ha^{-1}, respectively. The similarity of yield response to TKAN in both the cover crop and no cover crop treatment indicates no contribution or detraction of crop available N impacting corn yield following a cover crop.



Treatment	Equation	r^2	*p*-value
Cover Crop	$y=0.403+0.005x-1.181\times10^{-5}x^2$	0.85	<.001
No Cover Crop	$y=0.416+0.005x-1.171\times10^{-5}x^2$	0.67	<.001

Figure 4.1. Relative corn grain yield following a fall cover crop and no cover crop treatments averaged across replications at three environments in eastern North Dakota sites compared to total known available soil nitrogen.

Based on previous research, the lack of yield response to a previous cover crop is not unexpected (Andersen et al., 2020; Leiva, 2020; Ruark and Franzen, 2020). In a similar study established in Iowa with corn following a rye cover crop, Pantoja et al. (2015) noted a 6% decrease in corn yield following the cover crop treatment; however, the cover crop had no significant effect on yield-maximizing N rate, as also indicated in the present study (Figure 4.1). Without a differing relationship between following corn yield and TKAN between previous cover crop and no cover crop in this study, it appears N sequestered in cover crop biomass is not becoming available to the subsequent crop in this environment, as also noted by Andersen et al. (2020), Leiva (2020), and Ruark and Franzen, (2020). A Wisconsin study showed a corn yield increase and reduction on economic optimum N rate (EONR) in two out of three study years; however, differences in yield and EONR were mainly attributed to non-N related factors and rotation effects and not a direct contribution of N from cover crop biomass mineralization (Andraski and Bundy, 2005).

4.4.2. Wheat Yield and Quality

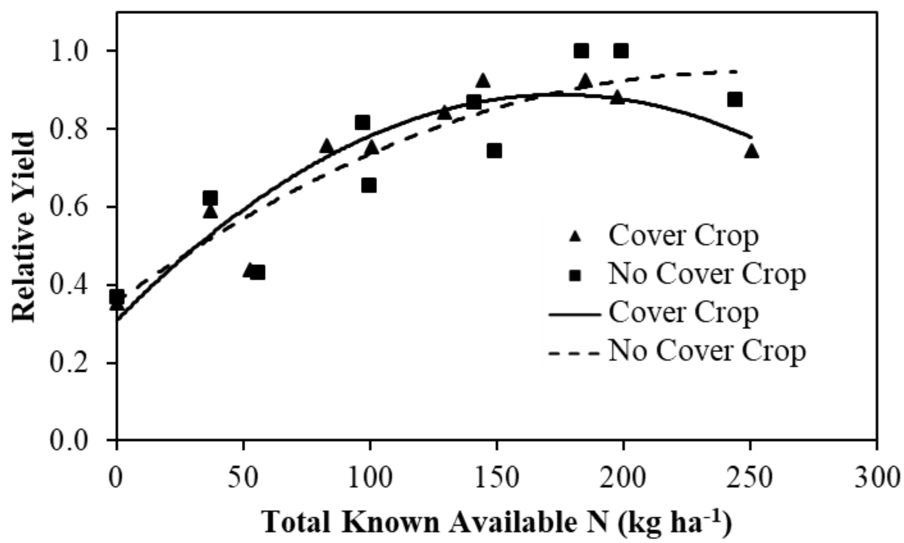
Similar to the response corn yield showed to the previous cover crop, wheat planted two cropping years following a fall cover crop showed a significant response to N fertilizer rate, but no response to cover crop treatment (Table 4.5). With increasing N fertilizer rate, not only did yield increase, but quality factors including test weight and grain protein content also showed a positive response (Table 4.5). Response of wheat yield, protein, and test weight to N is expected in this region (Otteson et al., 2008; Franzen, 2022b) and also reported in the barley planted prior to the cover crop on these sites (Goettl et al., 2024).

Table 4.5. Mean and standard deviation spring wheat yield, grain protein, and test weight planted following fall-seeded mixed species cover crops at three sites in eastern North Dakota.

Effect	**Variable**	**Yield**	**Test Weight**	**Grain Protein**
		kg ha^{-1}	kg m^{-3}	g kg^{-1}
Cover Crop (CC)	No Cover Crop	3380±1440	789±8	142±22
	Cover Crop	3270±1250	788±17	137±25
	p-value	.571	.782	.314
N Rate (kg ha^{-1})	180	4130±1510 a	793±25 a	164±15 a
	135	4070±1100 a	790±7 a	154±16 a
	90	3680±1070 a	791±8 a	141±18 ab
	45	2950±721 ab	789±8 a	123±13 b
	0	1780±431 b	780±7 b	114±7 b
	p-value	.049	.012	.007
CC x N Rate	*p*-value	.481	.793	.420

Note: Means with the same letter within the same effect are not significantly different at the *p*=.05 probability level.

Unlike the corn relative yield response to TKAN (Figure 4.1) where response curves follow similar quadratic shapes and have similar agronomic N rates, the wheat response to TKAN indicates differing responses to cover crop treatments (Figure 4.2). Whereas maximum wheat yield for the cover crop treatments was attained at 182 kg TKAN ha^{-1}, maximum yield on the non-cover crop treatment, attained by extrapolation, was reached at 263 kg TKAN ha^{-1}. Based on North Dakota N rate studies carried out from 1969-2019 (D. Franzen, personal communication, Jan 27, 2024) the TKAN needed to attain maximum yield averages of 249 kg ha^{-1} across all productivity levels and varying management practices in eastern North Dakota.



Treatment	Equation	r^2	*p*-value
Cover Crop	$y=0.307+0.007x-1.927\times10^{-5}x^2$	0.89	.001
No Cover Crop	$y=0.354+0.005x-9.487\times10^{-6}x^2$	0.81	.003

Figure 4.2. Relative wheat yield following a fall cover crop and no cover crop treatments averaged across replications at two environments in eastern North Dakota sites compared to total known available nitrogen.

Based on the historical wheat response to N in North Dakota and current recommendations, the TKAN rate for maximum yield on non-cover cropped treatments is near what is expected. The cover cropped treatment, however, requires a lower TKAN rate to attain maximum yield (Figure 4.2) indicating a potential contribution of N from the to the system not recognized in the constituents of TKAN calculation: soil NO_3-N, fertilizer N rate, or N credits (Eq 4.1) or by N fertilizer rate alone (Table 4.5). The contribution of N is only recognized two years following cover crop growth and termination, a phenomenon also noted in North Dakota by Franzen, (2022a). Additionally, the yield contribution may be from non-N-related cover crop benefits, such as increased snow capture during the winter prior to wheat planting, which was not measured in this study.

4.4.3. Nitrogen Pools

Soil N concentrations in the fall following cover crop growth and termination showed a significant decrease in NO_3-N in the cover cropped treatments at two of the three sites, however, NH_4-N and non-exchangeable NH_4-N showed no change (Table 4.6). Soil samples collected in the fall following corn harvest indicate no statistical differences in concentration of NO_3-N, (Table 4.7) for either cover crop treatment. Soil NO_3-N levels did show a significant interaction with N fertilizer rate in the fall following corn, prior to, and following wheat cultivation (Table 4.7). The spring and fall sampling occurrences, before and after wheat production, show no significant interactions between in any of the N pools as a result of cover crop treatment (Table 4.7).

Table 4.6. Soil NO_3-N, NH_4-H, and non-exchangeable NH_4-N sampled in the fall following mixed cover crop termination at three sites in eastern North Dakota. Soil samples were taken to a depth of 60 cm.

Site[a]	**Effect**	**Variable**	**NO_3-N**	**NH_4-N**	**Non-Ex NH_4-N**
			kg ha^{-1}		
LC	Cover Crop (CC)	No Cover Crop	70±50 a	23±9	1670±341
		Cover Crop	14±5 b	25±8	1690±252
		p-value	.004	.715	.862
	Fertilizer N Rate	*p*-value	.138	.595	.424
	CC x N Rate	*p*-value	.2843	.1782	.792
VC	Cover Crop (CC)	No Cover Crop	15±5		
		Cover Crop	12±5		
		p-value	.057		
	Fertilizer N Rate	*p*-value	.265		
	CC x N Rate	*p*-value	.815		
Gardner	Cover Crop	No Cover Crop	25±5 a	41±7	1950±35
		Cover Crop	6±3 b	36±6	1950±52
		p-value	.006	.046	.947

[a]Sites were located near Logan Center (LC), Valley City (VC) and Gardner North Dakota.
Note: Means with the same letter within the same effect are not significantly different at the .05 probability level.

Table 4.7. Soil NO_3-N, NH_4-N, and non-exchangeable NH_4-N concentrations sampled in the fall following corn harvest, prior to wheat plating the subsequent spring and again following wheat harvest. A mixed species cover crop was planted the fall prior to corn cultivation.

		Fall Following Corn[a]			**Spring Prior to Wheat[b]**			**Fall Following Wheat[b]**		
Effect	**Variable**	**NO_3-N**	**NH_4-N**	**Non-Ex NH_4-N**	**NO_3-N**	**NH_4-N**	**Non-Ex NH_4-N**	**NO_3-N**	**NH_4-N**	**Non-Ex NH_4-N**
		kg N ha^{-1}								
Cover Crop (CC)	No Cover Crop	33±27	34±13	1350±605	14±11	44±23	1190±555	28±25	28±9	1180±559
	Cover Crop	31±33	35±19	1310±554	12±9	41±31	1110±494	23±23	28±10	1120±533
	p-value	.775	.959	.179	.458	.811	.385	.343	.944	.286
N Rate (kg ha^{-1})	180	58±38 a	39±20	1320±604	21±12	53±43	1080±496	45±28 a	28±7	1110±550 b
	135	38±21 b	36±15	1320±551	17±9	40±20	1200±537	36±30 ab	30±9	1130±554 b
	90	36±3 bc	37±21	1360±592	13±11	47±32	1170±550	21±16 abc	29±10	1150±545 ab
	45	18±11 cd	31±9	1350±591	8±4	36±14	1180±529	14±8 bc	27±10	1190±561 a
	0	12±6 d	29±9	1300±593	7±4	36±12	1120±553	10±6 c	26±9	1160±568 ab
	p-value	<.001	.114	.473	.011	.398	.082	.013	.58	.014
CC x N Rate	*p*-value	.923	.202	.509	.111	.221	.807	.373	.746	.336

[a]Data from three sites were used in this analysis: Gardner, Valley City (VC), and Logan Center (LC).
[b]Data from two sites were used in this analysis: VC, and LC.
Note: Means with the same letter within the same effect are not significantly different at the.05 probability level.

As previously discussed, corn following a fall-seeded cover crop showed no yield response to the cover crop (Table 4.4), indicating the N sequestered in the cover crop biomass did not mineralize and become available to the crop during the following growing season. Similarly, soil N pools sampled in the fall following corn harvest, spring prior to wheat planting, and fall following wheat harvest showed no response to cover crop treatment (Table 4.7). The lack of significant differences in soil N as a result of the cover crop aligns with no yield response noted for both the corn and wheat (Table 4.4 and Table 4.5).

Although not statically significant when environment is treated as a random source of variation, as presented in Table 4.7, non-exchangeable NH_4-N concentration shows significant interaction with location and cover crop treatment when analyzed with location as a fixed source of variation (Table 4.8). The effect of location on cation-fixing capacity can be attributed to differences in soil texture and clay mineralogy (Steffens and Sparks, 1997; Franzen and Bu, 2018; Franzen, 2022a). Gardner showed the greatest levels of non-exchangeable NH_4-N at 2,000 kg ha^{-1}, followed by LC and VC with 1,610 kg ha^{-1} and 660 kg ha^{-1}, respectively, following corn harvest. Of the three sites in this study, Gardner had the highest smectitic and illitic clay ratio, which is a factor promoting NH_4^+ fixing capacity (Cox et al., 1996; Steffens and Sparks, 1997; Mulvaney, 2018; Franzen, 2022a). Concentration of non-exchangeable NH_4-N decreased at locations with overall lower clay levels.

Table 4.8. Soil non-exchangeable NH_4-N concentrations sampled in the fall following corn harvest, prior to wheat plating the subsequent spring and again following wheat harvest at three sites in eastern North Dakota. A mixed species cover crop was planted the fall prior to corn cultivation.

Effect	Variable	Post-Corn Harvest	Pre-Wheat Planting	Post-Wheat Harvest
		kg N ha^{-1}		
Environment[a] (Env)	Gardner[b]	2000±166 a		
	LC	1610±134 b	1640±236 a	1660±207 a
	VC	660±188 c	681±178 b	641±167 b
	p-value	<.001	<.001	<.001
Cover Crop (CC)	No Cover Crop	1350±605 a	1190±555 a	1180±559
	Cover Crop	1310±554 b	1110±494 b	1120±533
	p-value	.033	.015	.070
Fertilizer N Rate (N)	*p*-value	.642	.260	.739
CC x N	*p*-value	.463	.695	.797
Env x CC	*p*-value	.227	.101	.378
Env x N	*p*-value	.652	.936	.997
Env x CC x N	*p*-value	.653	.192	.900

[a]Sites were located near Logan Center (LC), Valley City (VC) and Gardner, North Dakota
[b]The Gardner environment was only sampled and analyzed in the fall following corn.
Note: Means with the same letter within the same effect are not significantly different at the *p*=.05 probability level.

Additionally, when environment is treated as a random source of variation, further interactions between cover crops and N pools are presented, site specifically (Table 4.8). Immediately following cover crop growth and termination, NH_4-N and non-exchangeable NH_4-N levels were statistically equal whereas NO_3-N was depressed in the cover crop treatments (Table 4.6, Table 4.8). In the subsequent samplings, however, NO_3-N and NH_4-N were not different based on cover crop treatment. Following corn and prior to wheat planting, non-exchangeable NH_4-N was greater in the non-cover crop treatments (Table 4.8). Although the kinetics causing NH_4^+ fixation relationship to cover crop growth are not known, this experiment proposes the impact does not occur during the period of cover crop growth, but rather following or during the time of cover crop decomposition and mineralization.

4.5. Conclusion

Although cover crops were shown to decrease residual NO_3-N in soil thereby decreasing the risk of leaching, the results of this study align with previous work indicating N sequestered in cover crop biomass does not become available the subsequent cropping season. Although a yield benefit from the cover crop was not seen, it is important to note a decrease in yield was not noted either. Planting a cover crop for soil health and environmental-service benefits did not come at a detriment to the following corn crop. In the second year following cover cropping practices, no yield benefit was realized; however, it does appear the cover crop has an impact on N response two cropping seasons following its growth. The lower N demand of the crop two years following a cover crop indicates a potential second-year credit from cover crops may be attained. Although the source of the N credit cannot be determined by the present study, future long-term studies should be carried out to determine the magnitude of this occurrence and its potential economic impact.

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5. THE IMPACT FIELD MANAGEMENT FOLLOWING BARLEY ON SOIL MOISTURE, TEMPERATURE, AND SURFACE ENERGY FACTORS

5.1. Abstract

In the Northern Great Plains, the period between small grain harvest and first killing frost leaves the soil unprotected, increasing vulnerability to erosion, especially if crop residue is removed or reduced by tillage. Integrating cover crops into production systems can mitigate erosion risk and improve soil health. However, in water-limited areas overwintering cover crops may reduce soil water content and residue may slow soil warming in the spring potentially leading to delayed planting. Understanding the impacts of crop residue and cover crops on spring surface energy balance will help quantify the impact they have on soil warming and moisture dynamics. Following barley three field management practices were established at a site in eastern North Dakota in the fall of 2022: 1) no cover crop control with barley residue, 2) no cover crop control with barley residue removed, 3) cereal rye and flax cover crop no-till drilled into barley residue producing 224 kg ha^{-1} of above ground spring biomass. Soil temperature, moisture, net radiation, and soil heat flux were monitored from April 18, 2023 until May 23, 2023. The presence of surface cover significantly impacted the soil energy balance and temperature compared to bare soil treatment. Bare soil exhibited the highest cumulative net radiation and soil heat flux, resulting in higher soil temperatures at the 3-cm depth averaging 9.3 ℃, compared to the no cover crop and cover crop treatments averaging 7.9 ℃ and 7.6 ℃, respectively. Although the mean soil temperature was greater, during periods of cooling the bare soil treatment had the lowest minimum temperature. Despite the expectation of cover crops to reduce soil moisture, no significant differences were observed, likely due to adequate precipitation during the study period and limited biomass accumulation.

5.2. Introduction

In the Northern Great Plains, small grain production systems leave the soil without growing vegetation for an average of 31 to 38 d, from the time of harvest to first killing frost (Table 5.1; (Jantzi et al., 2020)) along with the remainder of the fall and winter months until the succeeding cropping season. This unprotected surface leaves the soil vulnerable to wind and water erosion. By integrating cover crops into production systems, the growing cover crops and their carcasses following freeze-up will serve to reduce wind and water erosion, thus conserving soil and providing support for the growth of soil flora and fauna communities (Finney et al., 2017; Troch et al., 1999). The soil communities, in turn, improve soil aggregate stability and water infiltration (Chan & Heenan, 1999; USDA-NRCS, 2015). Additionally, the cover crop has the ability take up residual soil N and store it in its biomass, thus reducing nitrate losses (Chapter 3; Lee et al., 2016).

Table 5.1. Average number of days between the harvest of crops and first killing frost in North Dakota

Crop	Average harvest date[a]	Days between harvest and first killing frost[b]
Spring wheat	25 August	31
Durum	24 August	33
Barley	18 August 1	38

[a] Median date of most active usual harvesting dates, 20-year average (Jantzi et al., 2020)
[b]Average date of first -2.2°C frost across ND is September 26th (Jantzi et al., 2020)

In arid or other water-limited areas, however, the use of cover crops can lead to soil water depletion when used in place of a fallow-period (Holman et al., 2018). Conversely, an experiment in irrigated cotton in Texas reported higher volumetric soil water content following cover crops by virtue of increased water storage aided by the soil cover (Burke et al., 2021). The mixed results on the impact of cover crops on soil water content seems mostly to be driven by the environment in which they are implemented. To further understand the interaction of soil water and cover cropping practices, the energy factors driving evaporation need to be further understood.

The surface energy balance approach quantifies several energy pools responsible for driving water evaporation and heating the soil and air (O'Brien & Daigh, 2019). Energy is introduced into the systems through net solar radiation (R_n). The fraction of energy that warms the soil is quantified as soil surface heat flux (G). The difference between R_n and G is equal to latent heat flux (LE), which is the energy driving evaporation, and the sensible heat flux (H) energy emitted by the soil. Understanding these metrics has allowed for multidisciplinary approaches to understanding the transfer of heat and water within production agriculture and managed ecosystems (Ham et al., 1991; Kustas et al., 2019; Prueger et al., 1998; Sauer et al., 1998; Tanner, 1960).

Increased levels of surface cover or vegetation effectively reduce the amount of R_n input into the surface energy balance by virtue of higher reflectivity or energy interception by plants for photosynthesis (O'Brien & Daigh, 2019). Therefore, the reduction of surface cover, which facilitates increased R_n, requires an increase in G, LE, and/or H to complete the energy balance. The purpose of this research was to quantify the amount of R_n and G, thus identifying the energy available to govern soil processes such as evaporation (LE) and soil heating (H) under different soil cover and cover crop practices.

5.3. Methods and Materials

5.3.1. Site Description

The study was conducted in from summer 2022 to spring 2023 on an agricultural field in Grand Forks County, North Dakota (47.800261N, 97.769362W). The soil at this site was mapped as a Barnes loam (Fine-loamy, mixed, superactive, frigid Calcic Hapludolls) (Soil

Survey Staff, 2023); organic matter averaged 44 g kg^{-1}; sand, silt, and, clay 474 g kg^{-1}, 314 g kg^{-1}, and 212 g kg^{-1}, respectively; and bulk density 1.3 g cm^{-3}. The site was situated on a south-facing 1% slope. Located approximately 100 m from the experimental site was a North Dakota Agricultural Weather Network (NDAWN) weather station capable of monitoring precipitation, atmospheric pressure, temperature, humidity, solar radiation, wind, etc. (Table 5.2, Figure 5.1). The field was converted to no-tillage in 2019 and was managed under a conventional, non-irrigated, pinto bean-corn-soybean-barley rotation.

Table 5.2. Average maximum and minimum air temperature and total precipitation in Logan Center, North Dakota and their departure from the 30-yr average, as reported by the North Dakota Agricultural Weather Network (NDAWN, 2023).

	Air Temperature				**Precipitation**	
Date	**Average maximum**	**Departure from 30-year average**	**Average minimum**	**Departure from 30-year average**	**Total**	**Departure from 30-year average**
	°C				mm	
Jul 2022	26.4	0.0	15.1	1.1	54.4	-39.1
Aug 2022	26.0	-0.2	13.5	1.3	21.8	-47
Sep 2022	21.9	0.7	8.4	1.3	16.5	-40.6
Oct 2022	14.2	2.0	1.1	1.2	5.6	-40.6
Nov 2022	-0.2	-2.3	-8.8	-0.9	M	M
Dec 2022	-10.2	-4.6	-17.9	-2.9	M	M
Jan 2023	-8.0	1.0	-16.4	3.7	3.9	-7.3
Feb 2023	-6.8	-0.5	-17.8	-0.6	11.7	-1.0
Mar 2023	-6.4	-7.2	-16	-5.8	28.9	12.4
Apr 2023	3.8	-6.8	-4.2	-2	56.7	29.1
May 2023	23.2	4.4	8.8	3.3	50.7	-24.5

M: Denotes missing data

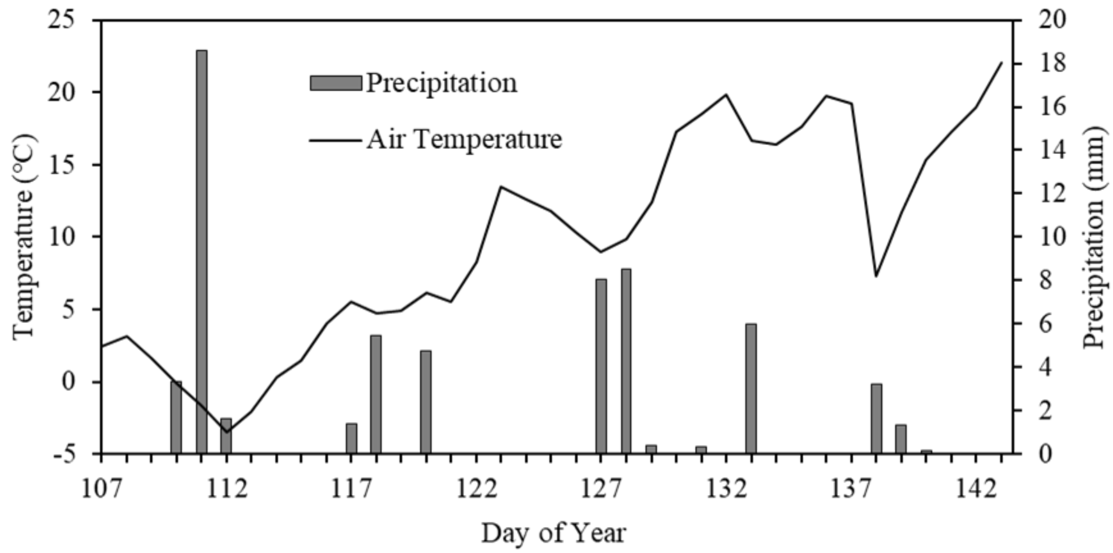

Figure 5.1. Average daily temperature and precipitation from day of year 108 (April 18, 2023) to DOY 143 (May 23, 2023) from the Logan Center North Dakota Agricultural Weather Network monitoring station (NDAWN, 2023).

5.3.2. Experimental Design

Three cover crop and soil surface treatments were established in this experiment: 1) no cover crop control with barley residue, 2) no cover crop control with barley residue removed, 3) full season cover crop no-till drilled into barley residue. The treatments were organized in a randomized complete block design with three replications with each experimental unit measuring 5.5 m by 5.5 m.

5.3.3. Cover Crop Management

The barley crop was harvested on August 26, 2022 with all straw and residue chopped and evenly spread across the plot area by the combine harvester. On September 1, 2022, 2.3 L ha^{-1} of glyphosate and 1.2 L ha^{-1} of 2,4-D ester was applied to terminate weeds present following the barley. To facilitate the size of the planting equipment, cover crops were no-till drilled in 19-cm rows into the entirety of the plot area. The cereal rye and brown flax cover crop was seeded at 22.4 kg ha^{-1} and 4.5 kg ha^{-1}, respectively. Due to the dry conditions at the time of cover crop planting, 11 mm of irrigation water was applied using a portable sprinkler system on Sept 14, 2022, to stimulate germination. Cover crops were chemically terminated on the no-cover crop treatments immediately following emergence using Roundup PowerMAX (Bayer CropScience) herbicide at the rate of 2.3 L ha^{-1}. Residue was raked and removed from the bare-soil treatment on September 9, 2022.

Residue coverage was measured following cover crop seeding using the line-transect method (Wollenhaupt & Pingry, 1991). Percent green ground cover was estimated using the Canopeo App (Oklahoma State University). Above ground cover crop biomass samples were collected on October 22, 2022, prior to the first anticipated killing frost and again on May 29, 2023. Cover crop biomass was collected from a 0.2 m^2 area, samples were then dried at 60 ℃ for 48 h and dry matter weight was determined. Care was taken to ensure the biomass was collected from an area of the experimental unit which would not impact the monitoring equipment.

5.3.4. Instrument and Data Collection

Soil heat flux was measured using a HFP01 soil heat flux plate (Campbell Scientific, INC) installed 6 cm below the soil surface (G_{6cm}) and a Type-T 24-gauge thermocouple was installed 3 cm below the soil surface, 3 cm directly above the heat flux plate. Both the flux plates and the thermocouple collected data every 30 min using CR10x dataloggers (Campbell Scientific, INC). Volumetric soil water content (θ_v) was measured 6 cm and 15 cm below the surface using 5MT water content and temperature probe and EM60 data logger (METER Group). Soil heat flux and θ_v was measured in each treatment in all replications. The combination method (Ochsner et al., 2007), which takes the heat capacity of the soil (C_{soil}), change in temperature (T), time (t) and depth (z) into consideration, was used to calculate the change in soil energy storage (ΔS) (Eq 5.1 and 5.2). C_{soil} was determined from the soil bulk density (ρ_b), fraction of mineral ($\Phi_{mineral}$) and organic matter (Φ_{om}), θ_v, and the heat capacities of soil solids (C_{soild}), water (C_w), organic matter (C_{om}), and mineral matter ($C_{mineral}$) (Eq 5.3 and 5.4), which in turn is used to calculate G (Eq 5.5).

$$\Delta S = XC_{soil} \tag{5.1}$$

$$X = \frac{\Delta T}{\Delta t} \times \Delta z \tag{5.2}$$

$$C_{soil} = \rho_b C_{solid} + C_w \theta_v \tag{5.3}$$

$$C_{solid} = C_{mineral}\Phi_{mineral} + C_{om}\Phi_{om} \tag{5.4}$$

$$G = \Delta S + G_{6cm} \tag{5.5}$$

Net solar radiation (R_n) is calculated as the total incoming short-wave radiation absorbed ($S_{absorved}$) and emitted ($S_{emitted}$) and long wave radiation absorbed ($L_{absorbed}$) and emitted ($L_{emitted}$) (Eq 5.6).

$$R_n = (S_{absorbed} - S_{emitted}) + (L_{absorbed} - L_{emitted}) \tag{5.6}$$

Solar radiation was measured with a NR-LITE2 net radiometer (Campbell Scientific, INC) mounted 1.5 m above the soil surface. Ground surface temperature was monitored using an SI-100 Infrared Radiometer (Apogee Instruments) mounted with the net radiometer, 1.5 m above the soil surface. Net solar radiation, due to equipment constraints, was only measured in one replication.

Available soil energy (AE) was calculated as the difference between R_n and G. The available soil energy is the sum of latent heat flux (LE) and sensible heat flux (H), energy pools capable of evaporating water and warming the air at the soil surface, respectively, combined quantitatively into available energy (Eq 5.7).

$$R_n - G = LE + H = AE \tag{5.7}$$

Instruments were installed on September 9, 2022. Soil heat flux plates, thermocouples, and 5MT moisture and moisture probes remained active through the winter. Net radiometers and

IRTs were removed on November 16, 2022 and reinstalled on April 17, 2023. All instrumentation was removed on May 23, 2023. Utilizing the NDAWN weather station near the site (ndawn.ndsu.nodak.edu), air temperature, precipitation, and wind speed data were collected throughout the duration of the study.

5.3.5. Data Analysis

Analysis of variance (ANOVA) was performed as randomized complete block design using JMP PRO 17 (SAS Institute) for daily mean soil temperature and moisture data. Replication (block) was treated as a random source of variation with day and treatment as fixed. Due to the lack of R_n measurement replication, data was averaged by day and presented for comparative purposes between the treatments. To estimate the amount of energy available to drive soil processes, the difference between net radiation (R_n) and soil heat flux (G) was calculated and reported.

5.4. Results and Discussion

5.4.1. Treatment Establishment

Following barley harvest, the chopped and spread barley straw from the combine provided 92% surface coverage on the cover crop and no cover crop treatments. When the loose residue was removed from the bare treatment, 43% ground cover remained from the post-harvest 6-10 cm tall barley stems.

Dry conditions during late summer and fall 2022 (Table 5.2) limited the amount of cover crop biomass and green ground cover compared to similar situations with more adequate rainfall (Chapter 3), producing 107 kg ha^{-1} above-ground biomass and 0.6% green ground cover at the time of frost termination on October 21, 2022. The following spring, the flax had winter terminated and only the cereal rye remained. The rye reached an average of 8.3% green ground cover on May 23, 2023 producing 224 kg ha^{-1} above ground biomass, which was also the day that all installed sensors were removed (Table 5.3).

5.4.2. Soil Temperature and Water Content

Monitoring began for the spring season on DOY 108 (April 18, 2023) as the soil at the 15 cm depth reached above freezing. During this warming period, the bare treatment had the highest temperature at the 3 cm depth, reaching a maximum of 8.8 ℃, followed by the no cover crop and cover crop treatments, which warmed to 5.7 ℃ and 3.6 ℃, respectively. From DOY 110 until DOY 113, the air temperature again dropped below 0 ℃ (Figure 1) (NDAWN, 2023) causing the soil profile to freeze once more. Beginning on DOY 114 (April 24, 2023) and continuing through the reminder of the monitoring period the average daily air temperature remained above 0 ℃ (NDAWN, 2023) and daily average soil temperature at all depths remained above freezing.

During the monitoring period from DOY 108 to 143, daily average temperature was significantly greater in the bare soil treatment averaging 9.3 ℃, compared to the no cover crop and cover crop treatments averaging 7.9 ℃ and 7.6 ℃, respectively, at the 3 cm soil depth (Table 5.3). As soil depth increased, average soil temperature was lower and exhibited less daily fluctuation in all treatments (Figure 5.2, Table 5.3). Regardless of depth, mean daily soil temperature was significantly greater in the bare treatment. In the upper two measured depths, 3 cm and 6 cm, the no cover crop treatment had a higher average temperature compared to the cover crop treatment (Table 5.3). In a similar study with wheat residue mulch, legume cover crop, and bare tilled treatments, Zhang et al. (2009) reported lower mean soil temperature during the cover crop growth period under the cover cropped treatment and greatest temperature in the bare-tilled treatment. In addition to having the greatest average temperature, the bare treatment also exhibited the greatest daily temperature fluctuation of all three treatments (Figure 5.2).

Daily minimum 3-cm temperature measured in the cover crop and no cover crop treatment was closely related during the study period (Figure 5.3). On average, the minimum temperature of the bare soil was greater than the mulched treatments; however, during periods of cooling, the bare soil treatment had a lower minimum temperature than the other treatments. The presence of a crop residue mulch (Fabrizzi et al., 2005; Olasantan, 1999; Zhang et al., 2009) or hydromulch (O'Brien et al., 2018) serves to reduce soil temperatures and daily temperature fluctuations compared to bare soil due to increased albedo and lower thermal conductivity, which then reduces the contribution of solar radiation to soil warming (Horton et al., 1996).

Table 5.3. Daily average soil temperature and volumetric water content (with standard deviation) from DOY 108 to 143 under three soil surface treatments: bare (all previous crop residue removed), no cover crop (crop residue remining), and cover crop (crop residue remaining with a no-till seeded cover crop) in eastern North Dakota.

			Soil Temperature		**Volumetric Water Content**	
Effect	**Variable**	**3 cm**	**6 cm**	**15 cm**	**6 cm**	**15 cm**
			————°C————		——cm^{-3} cm^{-3}——	
Treatment	Bare	9.3±6.8 a	9.0±6.5 a	7.6±5.9 a	.26±.04	.28±.03
	No Cover Crop	7.9±5.8 b	7.9±5.6 b	6.6±5.1 b	.27±.04	.26±.04
	Cover Crop	7.6±5.9 c	7.8±5.6 c	6.6±5.1 b	.27±.04	.26±.03
	p-value	<.001	.001	.005	.845	.486
Day	*p*-value	<.001	<.001	<.001	<.001	<.001
Day x Treatment	*p*-value	<.001	<.001	<.001	<.001	<.001

Note: Means with the same letter within column are not significantly different at $p = .05$.

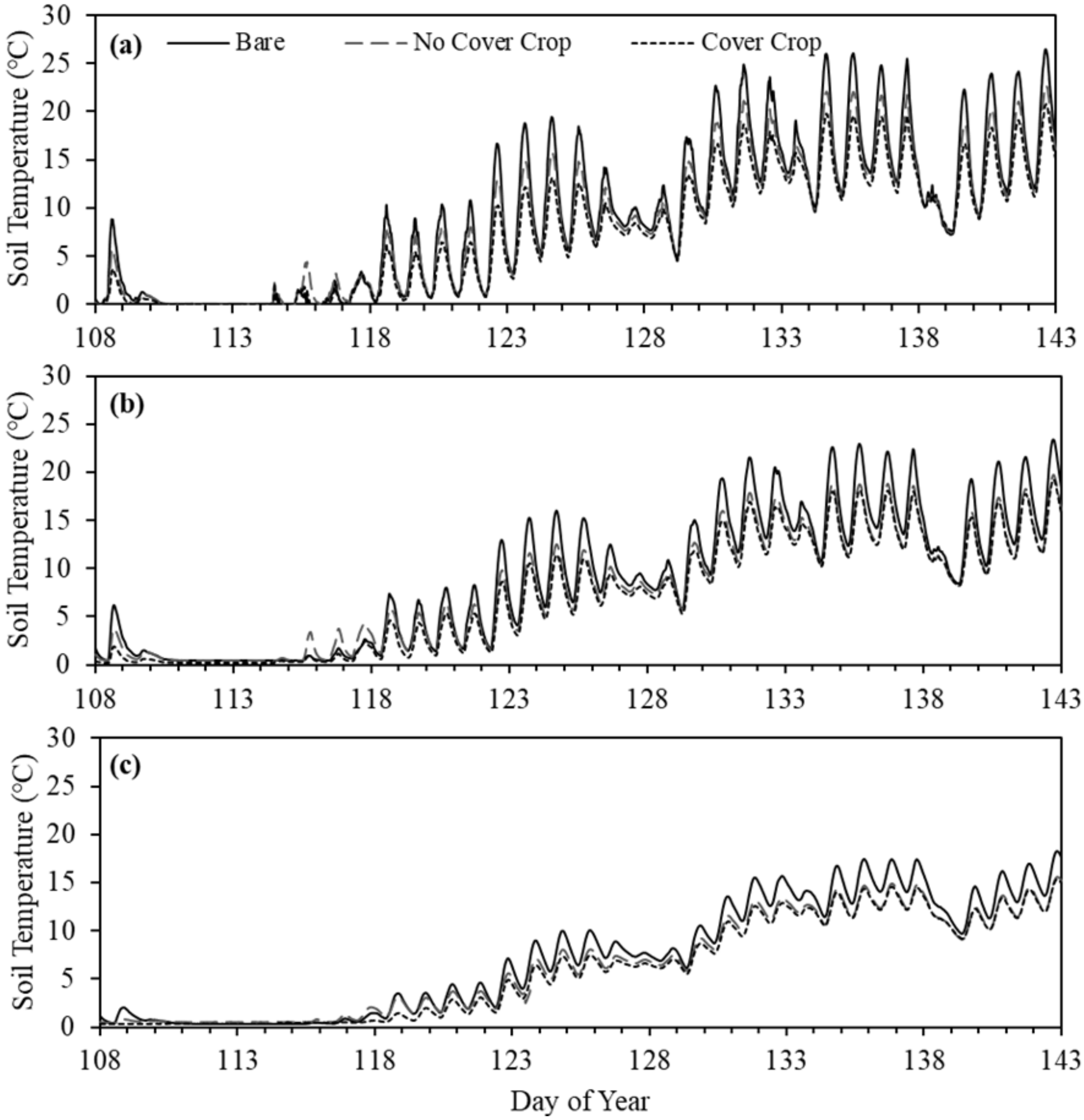

Figure 5.2. Soil temperature recorded in 30-minute intervals at 3 cm (a), 6 cm (b), and 15 cm (c) depths in three soil surface treatments: bare (all previous crop residue removed), no cover crop (crop residue remining), and cover crop (crop residue remaining with a no-till seeded cover crop) in eastern North Dakota.

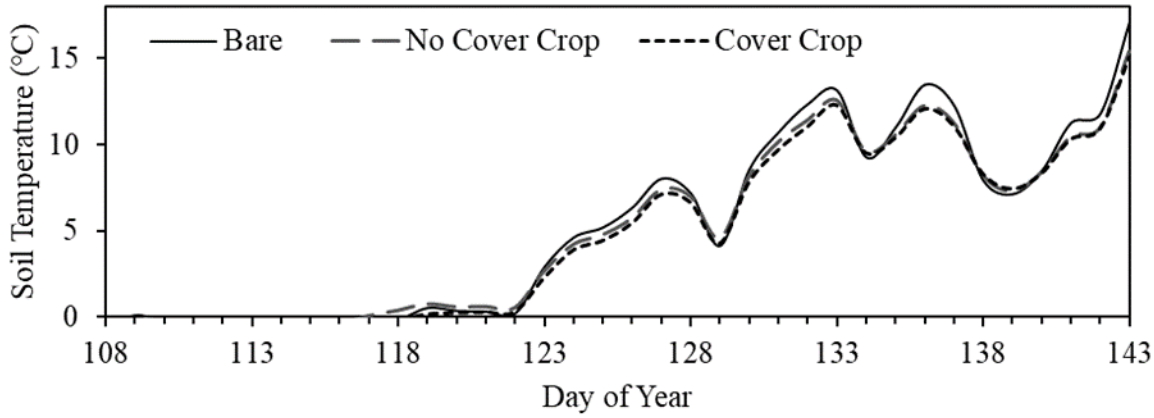

Figure 5.3. Minimum daily soil temperature at 3 cm depth in three soil surface treatments: bare (all previous crop residue removed), no cover crop (crop residue remining), and cover crop (crop residue remaining with a no-till seeded cover crop) in eastern North Dakota.

Although the crop residue served to reduce soil temperature, it did not have a statistically significant impact on daily average volumetric water content throughout the monitoring period (Table 5.3). The cover crop was expected to take up water from the soil profile and decrease water content compared to mulched non-cover cropped treatments, as reported in previous research (Holman et al., 2018; Zhang et al., 2007); however, this interaction was not noted in the present study (Table 5.3). The lack of impact of cover crops on soil water may be attributed to the above average and timely precipitation and the low cover crop biomass accumulation, which led to decreased demand for soil water (Table 5.2, Figure 5.1). The presence of surface cover was expected to reduce evaporation thereby increasing soil water content compared to bare soil (O'Brien et al., 2018; Olasantan, 1999; Zhang et al., 2007). However, during this study period, consistent and above average precipitation events (Table 5.2, Figure 5.1) may have masked potential differences from occurring. As can be seen in Figure 5.4, soil moisture content equalized following precipitation events and began to separate by treatment during the drying period. If a longer drying period had occurred, differences may have been noted, especially at the 6 cm depth.

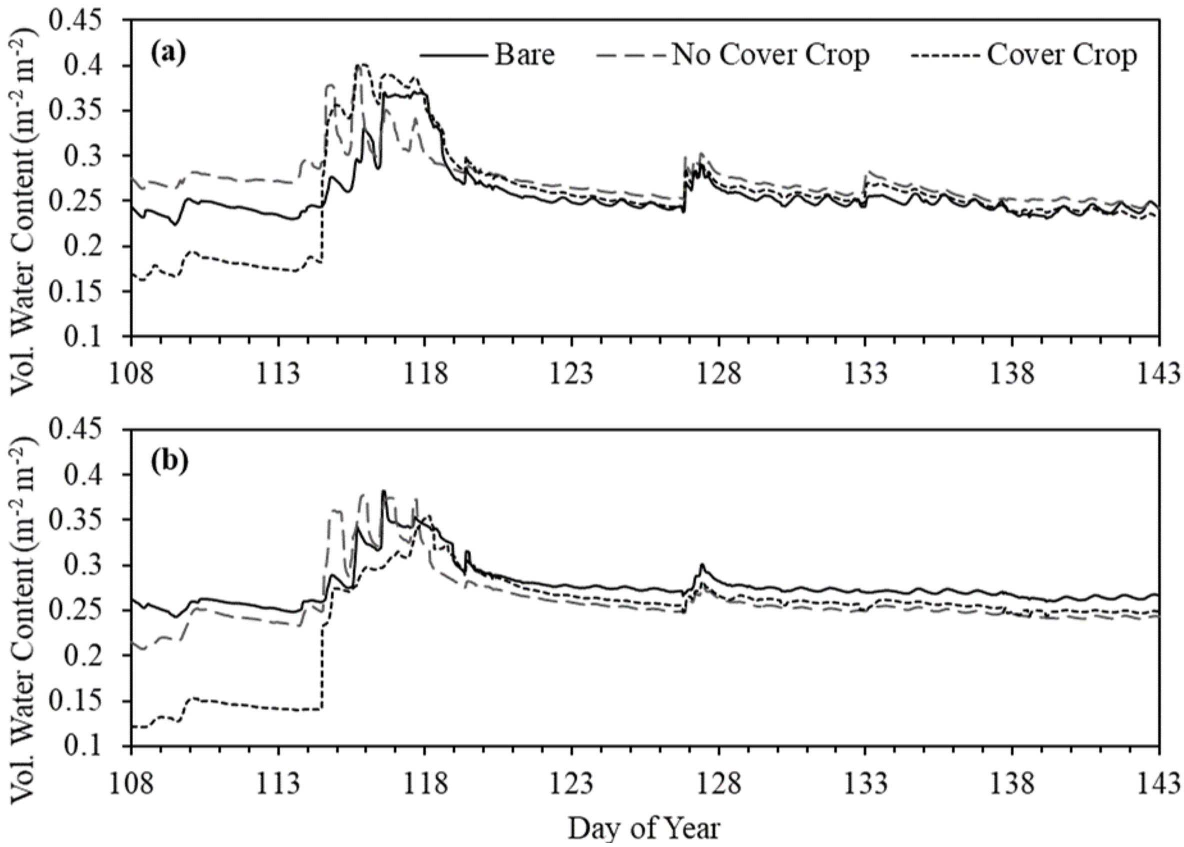

Figure 5.4. Soil volumetric water content recorded in 30-min intervals at 6 cm (a), and 15 cm (b) depth in three soil surface treatments: bare (all previous crop residue removed), no cover crop (crop residue remining), and cover crop (crop residue remaining with a no-till seeded cover crop) in eastern North Dakota.

5.4.3. Cumulative Fluxes

Although R_n measurements were not replicated and cannot be analyzed statistically, the general trend shows overall lower values in the no cover crop treatment, most notably in the second half of the monitoring period (Figure 5.5a). R_n in the bare and cover crop treatments trend more closely with 232.7 and 222.7 MJ m^{-2} cumulative totals, respectively. The no cover crop treatment had the lowest cumulative R_n, 188.9 MJ m^{-2}. Lower R_n in the cover crop and no cover crop treatment indicates greater reflection of solar radiation from the residue and vegetation. Crop residue and vegetation have a higher albedo compared to bare soil (Horton et al., 1996; O'Brien & Daigh, 2019), increased albedo of the surface increases reflectivity and decreases the amount of R_n reaching the soil surface (Horton et al., 1996; Irmak & Kukal, 2022; Sharratt &

Campbell, 1994). Higher R_n in the cover crop treatment compared to the no cover crop treatment can be attributed to the solar radiation absorbed by the growing crop to drive photosynthetic processes in addition to the higher albedo of the resudie .

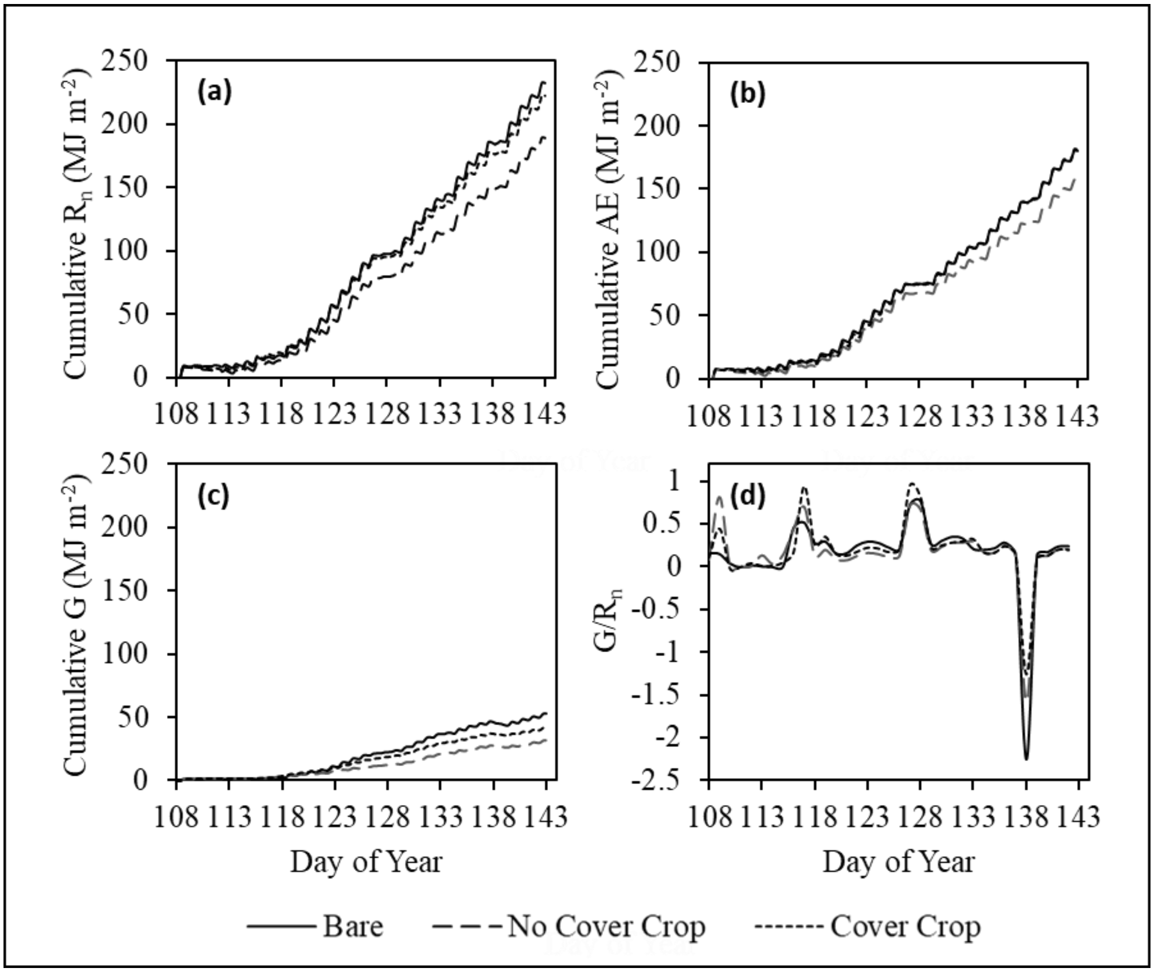

Figure 5.5. Cumulative R_n (a), cumulative AE (b), cumulative G (c), and G/R_n (d) in three soil surface treatments: bare (all previous crop residue removed), no cover crop (crop residue remining), and cover crop (crop residue remaining with a no-till seeded cover crop) in eastern North Dakota. R_n, AE, and G are plotted in 30-minute intervals, G/R_n is based on daily sum. R_n, net radiation; AE, available energy (R_n–G); G, soil heat flux.

In addition to reduced R_n, surface cover in this study also caused a reduction in soil heat flux (G). The bare treatment not only had the greatest cumulative G, 52.5 MJ m^{-2}, (Figure 5.5c) but also showed the greatest daily positive and negative G. The no cover crop treatment had the lowest cumulative G, 32.0 MJ m^{-2}, throughout the study period with the cover crop treatment remaining nearly in the middle with 41.6 MJ m^{-2} (Figure 5.5c). The response of soil G to the presence or absence to surface residue is twofold, first lower R_n to contribute to energy inputs and secondly decreased thermal conductivity of the residue buffers both heat gain and loss (Horton et al., 1996). Of the total energy from R_n, the fraction partitioned to G drives soil warming can be seen in the soil temperature dynamics noted in Table 5.3 and Figure 5.2.

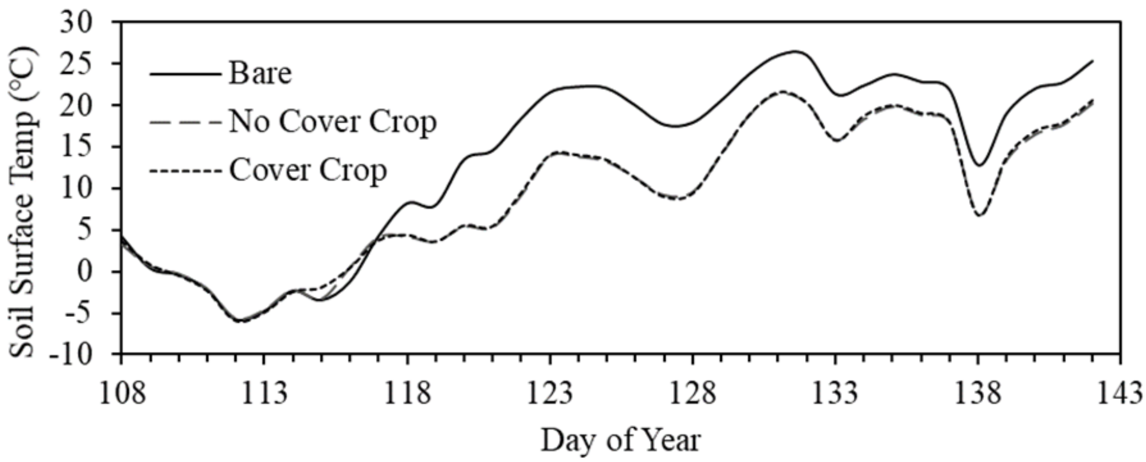

Figure 5.6. Ground surface temperature in three surface treatments: bare (all previous crop residue removed), no cover crop (crop residue remining), and cover crop (crop residue remaining with a no-till seeded cover crop) in eastern North Dakota.

Energy inputs into the system from R_n less the energy partitioned to G is equal to LE, energy to drive evaporative processes and H, heat loss to the atmosphere (Eq 5.7). Although the components of AE (LE and H) are not independently quantified in this study, several processes/measurements may be contributing to each factor thus impacting over all AE response. Overall, the no cover crop treatment had the lowest cumulative AE of the three surface treatments, with the bare and cover crop treatments having nearly overlapping responses (Figure 5.5b). In the bare treatment the soil surface temperature averaged 4.3 °C warmer than the other treatments (Figure 5.6) indicating H is likely higher in bare soil, as was demonstrated in studies which partitioned H and LE (Irmak & Kukal, 2022; O'Brien et al., 2018). The growing vegetation in the cover cropped treatment contributes to LE flux from plant transpiration in addition to evaporation occurring on all of the treatments, regardless of surface cover (Horton et al., 1996).

5.5. Management Implications

A commonly held concern among producers is cold, wet soils in the spring delaying crop planting and seed germination. To avoid this situation, tillage and residue removal practices are often employed. However, leaving fields without the protective cover of crop residue or cover crops creates an opportunity for soil erosion to occur. Based on this study, soil water content in the spring was not significantly different in either the bare, cover cropped, or residue treatments, even with the above average precipitation received. It is expected in dry spring conditions the mulch would help conserve water by reducing R_n and AE driving evaporation. The limited productivity of the cover crop in this study likely limited the interaction of this treatment on soil water and temperature; it is expected the cover crops may decrease soil moisture in some situations, but could not be ascertained from the current study.

Soil temperature was significantly different across all of the treatments, with the bare treatment resulting in the greatest average temperature, as expected. Although the bare treatment was, on average at the 3-cm depth, 1.4 and 1.7 °C greater than the mulched and cover cropped treatments, respectively, the bare treatment has the lowest minimum temperatures during cooling periods. In the event of a decrease in air temperature and more rapid negative G (cooling) from the bare soil, the lows experienced may be more damaging to seeds and seedlings than the benefits attained from the average warmer temperature.

From a management perspective, the erosion control and soil health benefits attained from residue and cover crops may outweigh the potentially lower average soil temperature compared to bare soil. The residue provides a degree of protection from rapid changes in temperature potentially mitigating seed damage in the event of a rapid decrease in air temperature following planting.

5.6. Conclusion

Although the cover crop productivity in this study was less than expected, it did have an impact on the energy balance compared to the bare and no cover crop treatments. The bare treatment resulted in the greatest cumulative R_n throughout the study period, followed by cover crop and no cover crop treatments. In addition to the highest cumulative energy input (R_n) the bare treatment had the greatest contribution of energy to drive soil heat flux (G), which can also be noted in the soil temperature data with statistically higher average temperatures noted in the bare treatment. No differences were noted in the soil moisture content for any of the three surface treatments, potentially due to adequate and timely precipitation during the study period. If spring precipitation was at or below average, larger differences in soil moisture would be expected. Additionally, more favorable cover crop biomass accumulation would likely impact each factor of the soil energy balance.

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6. INTERSEEDING COVER CROPS IN WIDE-ROW CORN[1,2]

6.1. Abstract

Cover crops are an effective way to reduce soil erosion and promote soil health. However, in North Dakota and other northern climates where corn (Zea mays L.) is an important commodity crop, killing frosts generally occur before harvest, leaving little opportunity for cover crop planting. By interseeding cover crops into corn during the growing season, the cover crops are given a longer period to establish. The purpose of this study was to identify the impact cover crops interseeded into wide-row (152-cm) corn have on soil water content and corn productivity. Two experimental sites were established in 2020 near Leonard and Rutland, ND. Both sites were organized into randomized complete block designs, with three cover crop treatments in Leonard (n = 9) and four cover crop treatments in Rutland (n=16). Cover crops were no-till drilled into the corn at the V4 growth stage. The cover crop treatments were diverse mixes developed to either provide pollinator habitat, overwinter, or winter-kill. Throughout the growing season, soil gravimetric water content and cover crop biomass was monitored. At the end of the growing season, dry cover crop biomass ranged from 212–1618 kg ha^{-1}. The presence and type of interseeded cover crops did not have a statistically significant effect on soil water content or corn yield. It is suspected the above average precipitation during the month of July led to adequate amounts of soil water for the entirety of the cover crop growing season, limiting the difference between treatments.

[1]The material in this chapter was co-authored by Brady Goettl, Bryce Andersen, Thomas DeSutter, David Franzen, and Abbey Wick. Brady Goettl and Bryce Anderson had primary responsibilities for conducting field work and collecting samples. Brady Goettl was the primary developer of the conclusions that are advanced here. Brady Goettl also drafted and revised all versions of this chapter. Thomas DeSutter, David Franzen, Bryce Andersen, and Abbey Wick served as proofreaders and checked the math in the statistical analysis conducted by Brady Goettl.
[2]Goettl, B., Andersen, B., DeSutter, T., Franzen, D., & Wick, A. (2024). Interseeded cover crops in wide-row corn: An opportunity for northern cropping systems. Crop, Forage & Turfgrass Management, e20268. https://doi.org/10.1002/cft2.20268

6.2. Introduction

Although the benefits of cover crops to soil health, erosion control, and weed suppression have been widely researched and recognized, producers still face difficulty identifying a time in their cropping rotation to facilitate cover crop establishment (CTIC, et al., 2020, 2023). For North Dakota and other northern regions with short growing seasons (average of 123 days above 0 °C in North Dakota), it is neither possible nor practical to plant a cover crop following the harvest of most major commodity crops, since killing frosts generally occur before cover crops can adequately grow (Jantzi et al., 2023; USDA National Agricultural Statistics Service, 2020). For example, active corn harvest in North Dakota ranges from October 8 to November 19, while average first killing frost occurs on September 28 (Jantzi et al., 2023). Therefore, in northern latitudes it is essential to explore other opportunities to establish cover crops; one such opportunity is cover crop interseeding. An issue faced with interseeding cover crops is competition between the cover crop and main crop for light, water, and nutrients (Magdoff & Van Es, 2009). This competition may result in decreased main crop yield or quality, in addition to poor cover crop establishment and stand.

Commonly, corn is planted in 76-cm rows to allow full canopy development, thus shading the ground and providing weed suppression (Nelson, 2014). If cover crops are to be established between the corn rows, lack of sunlight due to dense canopy cover is detrimental to their growth (Youngerman et al., 2018). To contend with this, corn rows can be increased in width, thus allowing more light to penetrate the corn canopy (Nelson, 2014). The practice of increasing the width of row-crop rows is known as double-skip row, skip-row, solar corridor, or simply 152-cm row (Nelson, 2014; Pavlista et al., 2010; Reinbeck & Kessel, 2019). Regarding the impact of increased row width on corn yield with no interseeded cover crop, mixed results have been reported, indicating further evaluation is needed (Lyon et al., 2009; Nelson, 2014; Pavlista et al., 2010; Thapa et al., 2018). In a North Dakota project, a 17% yield reduction was noted in wide-row corn compared to standard rows in non-interseeded treatments and 23% in interseeded treatments (Bibby, 2022).

As the importance of protecting environmental integrity, agricultural sustainability, and soil health increases, it is essential to implement conservation practices, such as cover cropping, on farm fields. Length of growing season in the northern states presents a great limitation to the implementation of cover crops, leading to limited adoption. With the high number of acres of land in corn production, finding a way to integrate cover crops on these acres would likely have the greatest impact. To aid in farmer adoption, the cover-cropping practice should be easy to implement, not affect crop yield too greatly, and have a high rate of success. Past experiments have shown promise with the practice of interseeding cover crops into 152-cm-row corn in regard to cover crop biomass production; however, mixed results have been noted in regards to effect on corn yield. The purpose of this study was to quantify the productivity of interseeded cover crops in wide-row (152-cm) corn and their effect on soil water content, weed pressure, and corn yield. The results of this study can be used by farmers and consultants who are interested in integrating cover crops following corn into their cropping rotations.

6.3. Methods and Materials

6.3.1. Site Descriptions

The experiments were conducted during the 2020 growing season at two sites in south-eastern North Dakota (Table 6.1). The sites were located near the towns of Leonard and Rutland (46.664934°N, 97.260809°W and 45.988379°N, 97.436121°W, respectively). The Leonard site was managed under no-till management for the previous 5 years growing a rotation of non-irrigated corn and soybean with soybean as the previous crop. The Rutland site was under no-tillage management for the past 40+ years. A diverse crop rotation has been implemented on this non-irrigated farm including wheat, rye, soybean, oilseed radish (*Raphanus sativus* L.), and corn, with the previous crop being soybean.

Table 6.1. Soil properties and growing season precipitation for two sites in south-eastern North Dakota.

	Soil Properties[a]		**Precipitation April-Sept[b]**		**Cumulative Corn GDD[bc]**	
Location	**Series**	**Texture**	**30-year Normal**	**Departure from Normal**	**30-year Normal**	**Departure from Normal**
			———mm———			
Leonard	Hecla	loamy fine sand	376	+32	2300	+121
Rutland	Overly	silty clay loam	376	+16	2190	+232

[a]Soil Survey Staff, 2023
[b]NDAWN, 2023
[c]Upper and lower temperature limits were 50°F (10°C) and 89°F (32°C), respectively, for the corn GDD calculation (NDAWN, 2023)

6.3.2. Experimental Design

Due to environmental constraints and the needs of the cooperating farmers, the number of treatments, blocks, and plot arrangements differed between the sites. Three cover crop mixes and a no-cover crop control were used at the Rutland site, while two cover crop mixes and a control were used in Leonard. The cover crop mixes and seeding rates were formulated using input from local practitioners and Extension specialists based on goals for the cover crop: pollinator, over-wintering, and overwintering plus warm season grasses (Table 6.2). Throughout the growing season, soil gravimetric water content (θ_g) was collected four times. Cover crop biomass was collected mid-season, at the time of corn tasseling and prior to the first killing frost. Corn grain yield and test weight were also determined.

Table 6.2. Cover crop species and amount of each included in cover crop mixes interseeded into wide-row corn in eastern North Dakota.

Pollinator Mix		**Overwinter Mix**		**Overwinter + Grass Mix**	
Species[a]	**Seeding Rate**	**Species**[b]	**Seeding Rate**	**Species**[c]	**Seeding Rate**
	kg ha^{-1}		kg ha^{-1}		kg ha^{-1}
Flax	2.2	Winter Rye	16.8	BMR Sorghum	2.2
Faba Bean	7.8	Red Clover	1.1	German Millet	3.4
Forage Oat	15	Vernal Alfalfa	2.2	Winter Rye	5.5
Austrian W. Pea	5.6			Red Clover	1.1
Crimson Clover	1.1			Vernal Alfalfa	2.2
Buckwheat	2.2				
Phacelia	2.2				
Forage Radish	1.1				

[a]*Linum usitatissimum* L., *Vicia faba* L., *Avena sativa* L., *Pisum sativum* L., *Trifolium incarnatum* L., *Fagopyrum esculentum* Moench, *Phacelia tanacetifolia* Benth., *Raphanus sativus* L.
[b]*Secale cereale* L., *Trifolium pratense* L., *Medicago sativa* L.
[c]*Sorghum bicolor* (L.) Moench, [*Setaria italica* (L.) P. Beauv]., *Secale cereale* L., *Trifolium pratense* L., *Medicago sativa* L.

The experiments were organized into a randomized complete block design with each experimental unit measuring 4.6 m by 12 m. Three cover crop treatments were used at the Leonard site, consisting of the pollinator and overwintering mix along with a no-cover crop check, organized into three blocks (n = 9). At the Rutland site, four blocks of the pollinator, overwintering, and overwintering plus warm-season grass cover crop mixes along with a no-cover crop check were established (n = 16).

6.3.3. Crop Management

At the Leonard site, Pioneer 9188 (91-day relative maturity; Pioneer Hi-bred International, Inc.) corn was planted on May 16, 2020, with a planting rate of 83,980 seeds ha^{-1}. Fertilizer was split-applied with 3 kg N, 12 kg P, and 3 kg K ha^{-1} (as 6–24–6 liquid fertilizer) applied in-furrow and 47 kg N ha^{-1} as 28% urea ammonium nitrate (UAN) side-banded at the time of planting. 120 kg N ha^{-1} of 28% UAN was Y-drop side-dressed at corn growth stage V4. Prior to cover crop interseeding, a 2.3 L ha^{-1} Roundup PowerMax (glyphosate, Bayer Cropscience LP) herbicide application was used to control weeds. Cover crops were interseeded on June 19, 2020, at the V4 growth stage using a modified hoe-type grain drill configured to plant four 30.4-cm rows between the rows of 152-cm corn.

Pioneer 9772AM (97-day relative maturity) corn was planted at the Rutland Site on May 16, 2020, in 15-cm twin-rows with a 152-cm inter-row spacing with a total planting population of 79,040 seeds ha^{-1}. The main source of fertility on this field was 22,400 kg ha^{-1} of fall-applied composted beef manure. Additional N in the form of 28% UAN was split applied; 67 kg N ha^{-1} was surface banded at the time of planting, followed by 45 kg N ha^{-1} applied in row at corn growth stage V5. To control weeds, an early post-emergence herbicide application of 55 mL ha^{-1} Impact (topramezone, AMVAC Chemical Corporation) and 0.42 kg ha^{-1} AAtrex Nine-O (atrazine, Syngenta Crop Protection, LLC) was made. Cover crop interseeding took place on June 19, 2020, at the V4 growth stage using a modified grain drill configured to plant six rows of cover crops between each corn row with 20 cm between the rows of cover crops.

6.3.4. Data Collection and Analysis

Starting on July 22, 2020, in Leonard and July 28, 2020, in Rutland, soil samples were taken for θ_g on 3-to-4-week intervals until mid-October. Sampling dates varied slightly due to rain events, with soil sampling performed only after a minimum of 2 days following significant rain events to allow for adequate excess water drainage. The soil samples were taken using a standard 2.5-cm soil probe to a depth of 15cm, halfway between the corn rows. The 5-to-15-cm depth was retained and analyzed using the thermogravimetric method to determine θ_g as outlined in (Dane et al., 2002).

Above ground cover crop and weed biomass samples were collected mid-season (July 22, 2020) at both locations. End of season biomass samples were taken on October 8, 2020 in Rutland and October 13, 2020 in Leonard with harvest timed prior to the first anticipated killing frost. From each experimental unit, a 0.5-m^2 biomass sample was taken (30-cm of row length in 152-cm row spacing), samples were then dried at 60°C for 48 h and dry matter weight was determined. Percent green ground cover was also quantified at the same timing as the biomass samples using the Canopeo App (Oklahoma State University). Care was taken to ensure corn green material was excluded from the measurements.

Corn was harvested on October 8, 2020, in Rutland and October 13, 2020, in Leonard by collecting the ears from one 12-m row within each experimental unit. After shelling, grain yield, test weight, and moisture content were determined. Grain harvest weights were adjusted to the standard moisture content of 15.5% for yield calculations.

Data analysis was performed using JMP Pro 17 (SAS Institute). Analysis of variance (ANOVA) was carried out as randomized complete block design; treatment was considered a fixed effect and replication (block) was considered a random effect. Levene's test was used to assess homogeneity of variances. When required, data was square-root transformed for analysis and back-transformed for reporting standard error of the mean for the transformed data was estimated using the delta method for reporting in the original scale. Mean separation was performed using Tukey's procedure. Data in this study was considered statistically significant at $p = .05$.

6.4. Results and Discussion

6.4.1. Crop Productivity

In this study, no statistical differences were noted for grain yield or test weight due to cover crop treatments at either location (Table 6.3), indicating presence or total biomass of the cover crops had no effect on corn productivity. Although management histories are not known, 2020 corn yield average for Cass and Sargent Counties, where this study took place, were 10,538 and 11,478 kg ha^{-1}, respectively; both countywide corn yield averages were lower than the 11,730 kg ha^{-1} at Leonard (Cass County) and 12,294 kg ha^{-1} at Rutland (Sargent County) (USDA National Agricultural Statistics Service, 2023). The findings of this study align with Iowa research which also noted no statistical interaction between presence of a cowpea [*Vigna unguiculata* (L.) Walp.], mung bean [*Vigna radiata* (L.) R. Wilczek], and sunn hemp (*Crotalaria juncea* L.) cover crop interseeded at V4 and yield in 60-inch corn (Reinbeck & Kessel, 2019). Also, interseeding camelina [*Camelina sativa* (L.) Crantz] into 76-cm corn rows at V4–V5 in North Dakota and Minnesota had no effect on corn yield (Berti et al., 2017). Franzen et al. (2023) noted no yield differences in 76-cm corn interseeded at V6–V8 with cereal rye at two eastern North Dakota sites. Similar experiments in Maryland, Pennsylvania, Iowa, Minnesota, North Dakota, and Michigan noted no significant yield penalty with interseeded cover crops (Brooker et al., 2020; Caswell et al., 2019; Mohammed et al., 2020).

Table 6.3. Mean values for corn grain yield and test weight, at each location for interseeded pollinator, overwinter, overwinter plus grass cover crop mixes, and no-cover crop treatments.

		Corn Grain	
Location	**Treatment**	**Yield**	**Test Weight**
		kg ha^{-1}	kg ha^{-1}
Leonard	Pollinator	12,107	721
	Overwinter	11,667	708
	No Cover Crop	12,107	708
	p-value	0.531	.371
	Standard Error	376	13
Rutland	Pollinator	12,483	734
	Overwinter	11,605	746
	Overwinter+Grass	12,357	746
	No Cover Crop	12,608	746
	p-value	.204	.869
	Standard Error	439	26

Productivity of the cover crop mixes differed between the sites and is variable within treatments, as represented by the standard error of the mean (Table 6.4). Although the variability of the treatments was not ideal, it is not unexpected, especially as it related to weed biomass and the propensity of weeds to exist in clusters. Recognizing the variability, several trends in cover crops establishment in wide-row corn can be noted.

At the Leonard and Rutland sites, greatest total end-of-season biomass was produced by the pollinator mix (1160 kg ha^{-1}), and the overwinter grass mix (1618 kg ha^{-1}), respectively. The low productivity of the pollinator mix at the Rutland site might be attributed to the forage radish constituent; at Leonard, radish produced 755 kg ha^{-1} of dry matter at the end of the growing season, while there was only 56 kg ha^{-1} at Rutland. These differences may be attributed to the corn herbicide program used at the Rutland site, which contained several residual herbicides as compared to the contact herbicide used prior to cover crop planting at Leonard. This interaction further highlights the need to consider herbicide program when selecting interseeded cover crop species (Wallace et al., 2017).

Mid-season green ground cover reflected cover crop biomass production, with the pollinator and overwinter+grass mixes having both the greatest biomass accumulation and providing 43%–44% green ground cover (Table 6.4). The mixes with less biomass accumulation had similar green cover as compared to the weeds growing in the no-cover crop treatments. The variability of weed pressure across all treatments makes it difficult to ascertain the contribution of the shading provided by this green ground cover on mid-season weed suppression, if any. By the end of the growing season, some plant species were undergoing senescence, resulting in a decrease in green cover compared to the mid-season measurements (Table 6.4); however, at the Leonard site, the pollinator mix still exhibited the greatest green growing cover and total biomass. Though the overwinter+grass mix at the Rutland site had the greatest biomass production, the low green cover of this treatment is a result of the senescence of the high-biomass German millet [*Setaria italica* (L.) P. Beauv] and BMR sorghum [*Sorghum bicolor* (L.) Moench], making the percent ground cover statistically comparable to the other cover crop treatments.

Table 6.4. Mean values for cover crop biomass, biomass of weeds, and percent green ground cover at each location for interseeded pollinator, overwinter, overwinter plus grass cover crop mixes, and no-cover crop treatments.

		Mid-Season			End of Season		
Location	**Treatment**	**Cover Crop Biomass**	**Weed Biomass**	**Green Ground Cover**	**Cover Crop Biomass**	**Weed Biomass**	**Green Ground Cover**
		kg ha^{-1}	kg ha^{-1}	%	kg ha^{-1}	kg ha^{-1}	%
Leonard	Pollinator	249 a	0 a	43 a	1160 a	64	40 a
	Overwinter	100 b	0 a	34 b	270 b	194	29 ab
	No Cover Crop		101 b	18 c		404	19 b
	p-Value	.002	.041	.002	.001	.141	.013
	Standard Error	28	19	3	111	131	3
Rutland	Pollinator	141 a	0	44 a	284 b	28	12 ab
	Overwinter	28 b	6	24 b	212 b	15	16 ab
	Overwinter+Grass	175 a	2	43 a	1618 a	27	24 a
	No Cover Crop		7	24 b		30	3b
	p-Value	.001	.795	.007	.011	.963	.021
	Standard Error	30	8	6	333	37	5

Note: Means with the same letter within columns at each site are not significantly different at p=.05.

Although there were significant differences in the biomass produced by the differing cover crop mixes, there were no significant differences in the biomass of weeds at the end of the season (Table 6.4). Additionally, weed pressure was highly variable across experimental units, as indicated by the standard deviation. Studies by Uchino et al. (2012) and Youngerman et al. (2018) reported a suppressive effect of interseeded cover crops on inter-row weeds in corn; however, standard (76-cm) row spacings were used in these studies. Narrower row widths may provide greater weed suppression as compared to wide rows (Nelson, 2014). The increased light infiltration in the 152-cm rows compared to 76-cm rows (Bibby, 2022; Nelson, 2014) may have contributed to the lack of suppressive effect of cover crops in this study along with the high variation which may have masked potential treatment differences.

When comparing the amount of cover crop biomass accumulated in this study to other studies which interseeded cover crops into corn, using various other methods, the practices used in this study show promise for increasing fall cover crop biomass. In two studies also carried out North Dakota, Franzen et al. (2023) reported cover crop biomass accumulation ranging from 69 to 351 kg ha^{-1} and Mohammed et al. (2020) 66–113 kg ha^{-1} of interseeded winter annual fall-biomass accumulation in 76-cm corn. A similar study with a site in North Dakota interseeding camelina into 60- and 76-cm corn Berti et al. (2017) reported fall ground cover ranging from 9–14%, compared to the 12–40% cover noted in this study. Increasing corn row spacing to 152-cm, as done in this study, may increase the potential for greater interseeded cover crop biomass accumulation as compared to standard, 30-inch row spacing.

6.4.2. Soil Water

At both the Leonard and Rutland sites, no trends were noted on the effect of interseeded cover crops on soil θ_g. When averaged across all sampling dates, there were no significant differences in θ_g across any of the cover crop treatments (Table 6.5). Time was the only effect of significance, which was a function of the amount of precipitation received prior to sampling and timing of sampling following wetting or drying events (Table 6.5). The absence of interaction between interseeded cover crops and θ_g may be attributed to the above average precipitation received during the experiment (Table 6.1). At both experimental sites, July rainfall was more than 76 mm above average, leading to no water-limiting conditions during the cover crop growth period (NDAWN, 2023). Similar to the results presented here, research in 30-inch corn reported no significant difference in soil moisture content under interseeded cover crop and no-cover crop treatments (Mohammed et al., 2020). St Aime et al. (2023) asserts the water used by cover crops is balanced by the increased infiltration and soil water holding capacity they provide, which contributes to no difference in cover crop and non-cover crops treatments in years with above-average precipitation.

Table 6.5. Mean values of soil gravimetric water content (θ_g) sampled four times through the corn growing season at two sites in south-eastern North Dakota for interseeded pollinator, overwinter, overwinter plus grass cover crop mixes, and no-cover crop treatments.

Location	**Effect**	**Variable**	**θ_g**
			%
Leonard	Treatment	Pollinator	16
		Overwinter	16
		No Cover Crop	17
		p-value	.932
	Time	*p*-value	<.001
	Time x Treatment	*p*-value	.121
Rutland	Treatment	Pollinator	33
		Overwinter	34
		Overwinter+Grass	34
		No Cover Crop	34
		p-value	.478
	Time	*p*-value	.001
	Time x Treatment	*p*-value	.166

In cropping systems where cover crops are established and provide surface cover, benefits to soil water content have been noted, including trends toward reduced evapotranspiration (Schomberg et al., 2023). However, increasing row width increases the amount of solar radiation reaching the soil surface (Nelson, 2014; Youngerman et al., 2018), which while beneficial to interseeded cover crops, increases the potential for evaporation from bare soil (O'Brien & Daigh, 2019). Research on wide-row corn production shows increased inter-row soil moisture attributed to slower root exploration (Abunyewa et al., 2010; Lyon et al., 2009; Pavlista et al., 2010), which Lyon et al. (2009) reported is only beneficial to crop productivity in areas with expected yields less than 6,273 kg ha^{-1}. Although no statistical differences in water content were noted in this and other experiments, care should be taken when this wide-row system is implemented in drought conditions, especially if poor cover crop establishment is experienced.

6.5. Conclusion

The results of these experiments show promise for the establishment and biomass production of interseeded cover crops in 152-cm, wide-row corn without affecting grain yield. With the limited growing season in the Northern Great Plains, sowing a cover crop following corn harvest is not a viable option, and results from previous studies interseeding cover crops in 30-inch corn show limited biomass accumulation compared to this study. The cover crop biomass produced and potential environmental services provided may help to promote soil health, decrease soil erosion, and support pollinators. However, increasing the row-width of corn may lead to a decrease in total grain yield and an increase in weed pressure where cover crop establishment is poor compared to standard row widths. The decrease in yield and profitability of this system must be weighed against the benefits of cover crop establishment and their value added to the particular farming operation. Future studies should be carried out on this topic in order to develop a more consistent dataset from which to draw conclusions about the impact of corn row-width and interseeded cover crops on crop productivity through the lens of farm economics and value of potential environmental services.

6.6. References

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7. GENERAL CONCLUSION

In North Dakota cropping systems, proper management of nutrients and prevention of soil erosion should be of the utmost importance if long-term productivity is to be sustained. By integrating barley into the cropping rotations, plant diversity can be increased not only through the additional crop, but also through the opportunity to integrate cover crops. The cover crops allow residual NO_3-N to be managed, thereby decreasing leaching loss in addition to providing soil health and erosion control benefits.

The proper management of N in barley not only decreases input costs to the producer and maximizes net returns, but also optimizes grain quality for malting, bringing potential opportunities for grain premiums. Using the economic optimum N rate approach for N recommendations brings a twofold benefit: maximizing farmer profitability and decreasing dependence on N fertilizer by maximizing efficiency. With increased efficiency, residual soil NO_3-N following barley harvest can be minimized. Given an average of 38 days between barley harvest and first killing frost, adequate growing season is available to grow a low-cost small grain cover crop, taking advantage of volunteer barley growth. The cover crop has been shown to reduce the fall NO_3-N, preventing leaching loss. In addition to the soil health benefits attained from the cover crop, it is not detrimental to the following crop yield and causes minimal disruption to soil water content the following spring. Preliminary results show an N credit may be available the second year following cover crops, potentially indicating an N-rate reduction is attainable in cover cropped production systems.

By properly managing N, maximizing soil health, and minimizing soil degradation through diversified cropping systems and cover crops, North Dakota will continue to be one of the top agricultural states in the US through productive sustainability.

APPENDIX: RESULTS OF 2020 COVER CROPS FOLLOWING TWO-ROW MALTING BARLEY

A.1. Methods and Materials

A.1.1. Site Description

The on-farm experiments took place during 2020 growing season at two non-irrigated, no-till experimental sites located in Grand Forks and Barnes Counties in North Dakota, near Logan Center (LC) and Valley City (VC), respectively (Table A1). The VC site had been under no-till management for over 40 years, producing several rotational crops including corn, soybean, oil-seed sunflower, six-row malting barley, and hard red spring wheat. Oil-seed sunflower was previous crop at the VC site (46.88403N, 97.915529W). The LC site (47.795544N, 97.773766W) was transitioned to no-till management less than 5 years before the establishment of the experiment. Crops in rotation consisted of pinto bean, soybean, six-row malting barley, and hard red spring wheat. The previous crop on the LC sites was pinto bean.

Table A1. Soil properties and chemical analyses for each experimental location, measured in April 2020 prior to barley seeding. NO_3-N was sampled to a depth of 60 cm while samples were taken to a depth of 15 cm for P, K, pH, and organic matter.

Site[a]	Series	Texture	NO_3-N	P	K	pH	OM
			kg ha^{-1}	mg kg^{-1}	mg kg^{-1}		g kg^{-1}
VC2020	Swenoda[b]	sandy loam	43	27	201	5.2	26
LC2020	Barnes[c]	loam	47	15	282	6.7	39

[a]Sites were located near Logan Center (LC), Valley City (VC) and Gardner, North Dakota
[b]Coarse-loamy, mixed, superactive, frigid Pachic Hapludolls (Soil Survey Staff, 2023)
[c]Fine-loamy, mixed, superactive, frigid Calcic Hapludolls (Soil Survey Staff, 2023)

Precipitation at the LC site was below normal for the period of cover crop growth during the 2020 season (Table A2) (NDAWN, 2023), as a result germination and biomass production were much poorer than anticipated and soil sample collection for NO_3-N analysis became unreasonably difficult. At the VC site, precipitation was above normal early in the cover crop growing season (NDAWN, 2023) providing moisture for cover crop establishment before falling below normal during September and October.

Table A2. Average air temperature and total precipitation at two sites in North Dakota based on 30-yr average and their departure from the average for each growing season, as reported by the North Dakota Agricultural Weather Network (NDAWN, 2023)

		Site[a]			
		LC[b]		**VC[c]**	
Year	**Month**	**30-yr Average**	**Departure from 30-yr Average**	**30-yr Average**	**Departure from 30-yr Average**
		Air Temperature			
		°C			
2020	Apr.	4.2	-2.4	5.6	-2.5
	May	12.1	-1.3	13.2	-1.6
	June	17.8	2.2	19.0	2.0
	July	20.2	1.1	21.4	1.0
	Aug.	19.2	0.2	20.3	0.0
	Sept.	14.1	-0.7	15.3	-1.0
	Oct.	6.0	-3.8	7.4	-3.9
		Total Precipitation			
		mm			
2020	Apr.	27.7	-7.5	35.6	-13.5
	May	75.2	-38.9	81.0	-43.9
	June	95.5	43.0	94.5	19.6
	July	93.5	9.9	79.0	68.9
	Aug.	68.8	-49.3	65.0	25.0
	Sept.	57.2	-50.5	67.3	-51.1
	Oct	46.2	-35.1	50.8	-42.7

[a]Sites were located near Logan Center (LC) and Valley City (VC), North Dakota.
[b]Data from the Logan Center NDAWN weather station, 1.3 km from the LC site.
[c]Data from the Fingal NDAWN weather station, 14.5 km from the VC site.

A.1.2. Experimental Design

Experimental design follows the protocol as described in Section 3.3.2.

A.1.3. Barley Management

Barley was no-till drilled on May 6, 2020 at both the LC and VC site and harvested on August 10, 2020 at the VC site, August 18, 2020 at LC. All other barley management practices follow those used in 2021 and are presented in Section 3.3.3.

A.1.4. Cover Crop Management

Following the harvest of the barley crop, mixed species cover crops (Table A.3) were no-till drilled in 19-cm rows on August 20, 2020 at LC, August 25, 2020 at VC. To assist with nodulation of the faba bean, N-Charge Pea/Vetch/Lentil inoculant (Verdesian Life Sciences) was mixed with the seed to prior to planting at the recommended rate of 70.8 g per 22.7 kg of seed (Verdesian Life Sciences, 2015). At both sites, volunteer barley was allowed to grow with the cover crops. To facilitate planting, all plots were sown with a cover crop. On September 10, 2020, 2.3 L ha^{-1} Roundup PowerMAX (Bayer CropScience) was applied to terminate the emerged cover crops on the no-cover crop plots.

Table A3. Cover crop species and seeding rates at two experimental sites in eastern North Dakota

Site[a]	Species	Seeding rate
		kg ha^{-1}
VC2020	Forage Radish	2.2
	Brown Flax	2.2
	Faba bean	33.6
	Barley	Volunteer
LC2020	Forage Radish	2.2
	Brown Flax	2.2
	Faba bean	33.6
	Cereal rye	44.8
	Barley	Volunteer

[a]Sites were located near Logan Center (LC) and Valley City (VC), North Dakota

A.1.5. Data Collection and Analysis

Above ground cover crop biomass was collected on October 14, 2020 at both sites, timed prior to the first anticipated killing frost. Biomass samples were taken from three 0.2-m^2 area in each main plot and combined to represent one 0.6 m^2 sample. Cover crops were then separated by species for further analysis. After the samples were dried at 60℃ for 48 h, dry matter weight was determined. Samples were then ground and analyzed for total N content using an XDS Rapid Content Analyzer (FOSS).

Soil to be tested for NO_3-N was sampled to a depth of 60 cm at VC and 45 cm at LC in each experimental unit following barley harvest, prior to cover crop planting. Soil samples were analyzed by the NDSU Soil Testing Laboratory using the water extractant method (Nathan and Gelderman, 2012; Franzen, 2018).

Soil aggregate stability and aggregate size distribution was measured in the spring of 2021. Sub-samples were randomly collected from a depth of 0-5 cm and combined to make one sample for each of the main plots. Aggregate stability was determined using the method described in Section 3.3.5.

Data analysis was performed using JMP Pro 17 (SAS Institute). Analysis of variance (ANOVA) was carried out as a randomized complete block design for residual NO_3-N prior to cover crop planting, cover crop biomass, and aggregate stability data. In all analyses, replication (block) was considered a random effect. Location, N-rate, cover crop treatment, and cover crop species were considered fixed effects, where applicable. Homogeneity of the variance was determined if the ratio of the largest variance to the smallest is 10 or less (C. Doetkott, personal communication, Dec. 18, 2023) Mean separation was performed using Tukey's Procedure. Data in this study was considered statistically significant at $p \leq .05$.

A.2. Results and Discussion

Since only the LC site was seeded with cereal rye as part of the cover crop mix, a statistical comparison cannot be conducted; however, based on the trend, the mixed species cover crop at the VC site produced more above-ground biomass compared to LC (Table A4), which may be attributed to the more severe drought conditions at the LC site (Table A2).

Table A4. Mean and standard deviation above ground biomass production and N content of an eastern North Dakota mixed species cover crop planted following barley.

Site[a]	Species	Biomass	Biomass N content
		kg ha^{-1}	
VC	Forage Radish	278±80	3±0
	Brown Flax	11±9	0±0
	Faba Bean	56±23	1±1
	Barley	749±438	15±5
	Total Biomass	1,090±479	25±6
LC	Radish	28±38	3±0
	Flax	0±0	0±0
	Faba Bean	10±21	0±1
	Barley and Rye	235±230	4±4
	Total Biomass	272±247	5±4

[a]Sites were located near Logan Center (LC), Valley City (VC) and Gardner, North Dakota.

Due to the dry conditions at the LC site, soil samples for NO_3-N analysis were only able to be collected to a depth of 45 cm compared to 60 cm at the VC site. At LC, no differences were noted in NO_3-N following the crop of barley for any of the five fertilizer-N treatments, with all results being considerably low (Table A5). A response to fertilizer N was noted at the VC site, specifically at the higher N-fertilizer rates (Table A5).

Table A5. Soil NO_3-N concentration means and standard deviation following two-row malting barley harvest at two eastern-North Dakota experimental site. Five fertilizer N rates were applied to the barley at the time of planting ranging from 0-180 kg N ha^{-1}.

Site[a]	**N Rate**	**NO_3-N**
	———kg ha^{-1}———	
LC	180	22±14
	135	14±9
	90	15±5
	45	17±11
	0	17±9
	p-value	.417
VC	180	46±13 a
	135	43±14 ab
	90	35±12 b
	45	35±10 b
	0	34±8 b
	p-value	.041

[a]Sites were located near Logan Center (LC) and Valley City (VC), North Dakota
Note: Means with the same letter within each location are not significantly different at p=.05.

Comparing the cover crop and no cover crop treatments, no differences in percent water stable aggregates (WSA) were noted in 2020. The VC site had lower WSA for the 53 µm aggregate fraction and total aggregation compared to LC (Table A6). The conditions at the VC sites are less conducive to aggregation due to low OM levels, coarse texture. Although VC has lower WSA, both sites are still near favorable ranges (Soil Quality Institute, 1999; Moebius-Clune et al., 2016).

Table A6. Mean and standard deviation percent water stable aggregates sampled the spring following cover crop and no-cover crop treatments at two locations in eastern North Dakota.

		Soil Aggregate Size Fraction			
Effect	**Variable**	**2000 µm**	**250 µm**	**53 µm**	**>53 µm**
		%			
Location[a] (Loc)	LC	5±2 b	30±2	20±2 a	56±3 a
	VC	11±3 a	26±4	11±2 b	49±5 b
	p-value	.001	.051	<.001	.006
Cover Crop (CC)	No Cover Crop	8±5	29±3	16±6	53±4
	Cover Crop	8±3	28±5	16±5	52±7
	p-value	.982	.575	.775	.688
Loc x CC	*p*-value	.306	.168	.295	.278

[a]Sites were located near Logan Center (LC) and Valley City (VC), North Dakota

Note: Means with the same letter within the same effect are not significantly different at the p=.05 probability level.

A.3. References

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