NITROGEN FERTILIZER TYPES AND APPLICATION TIMING ON HARD RED SPRING WHEAT PRODUCTIVITY AND GRAIN PROTEIN

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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

MASTER OF SCIENCE

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ABSTRACT

The balance of improving hard red spring wheat (*Triticum aestivum* L. emend Thell) yield while maintaining grain protein concentration continues to be a challenge in agriculture. The objective of the field research was to evaluate N fertilizer types, additives, rates, and application timing to find N management strategies that improved the efficiency of the applied N with regards to both grain protein and yield. Another aspect of this study was to determine if ground-based active sensor data can predict grain yield and/or protein content. Fertilizer treatments consisted of 2 application timings, 3 sources of N, 3 rates of N, and 2 additive types. Spring applications improved grain protein and yield compared to fall applications. Polymer coated urea shows promise in improving grain protein over urea alone. However, profitability is dependent on environmental factors that may influence N availability, as well as prices at the time that the grain is marketed.

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DEDICATION

Dedicated to the memories of my Grandfathers, Robert Basil Preskey (1935-2015) and Gaylord Thomas Feland (1938-2016).

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Grain protein concentration and grain yield are two major components influencing the end-use value of hard red spring wheat (HRSW). Due to the inverse relationship of grain protein concentration and grain yield with currently available cultivars, these components are difficult to improve simultaneously. A way to counteract this negative correlation is to improve agronomic practices in regard to nitrogen (N) management. Management choices to address this challenge have become more numerous in recent years with different application timings, application rates, and N fertilizer sources. The profitability of these options, however, is impacted by the cost associated with their application.

The goal of a successful N management system is to increase the efficiency of nitrogenous fertilizers and to minimize any possible adverse environmental effects by reducing N losses through volatilization, denitrification, run off, and leaching. Efficiency of N fertilizers can be achieved with the use of appropriate fertilizer types, rates, and timing. Environmental and economic issues have increased the need to better understand the role of N fertilizers in HRSW production and their behavior in the soil.

LITERATURE REVIEW

Nitrogen Fertilizer in Relation to Wheat Grain Protein

Nitrogen is available to plants as either ammonium (NH_4^+) or nitrate (NO_3^-) and is subject to several transformations when added to soil as fertilizer. These transformations influence N availability to plants as well as the potential movement of N to water supplies when NO_3^- is the result of the transformation (Lamb, 2014).

Many factors influence the transformation and movement of N in the soil, such as temperature, moisture, soil pH and soil type (Lamb, 2014). Understanding the biological and chemical transformations of N in the soil are critical when developing N programs to optimize grain yield and protein concentration, as well as anticipating possible environmental effects.

Grain protein concentration is an important quality factor that affects the marketability of wheat in the Unites States. Low grain protein can result in a financial loss to producers, especially in years with high protein discounts. Higher protein HRSW (*Triticum aestivum* L. emend Thell) is frequently marketed at a premium compared to lower protein wheat of the same market class. When high protein wheat is limited within the greater market, a high protein premium offered by a point of sale may represent 50% or more of the market price of the crop (Brown et al., 2005). Protein levels in winter wheat regions as well as average protein levels from spring wheat regions are factors that impact premiums and discounts when farmers market grain. Since higher yielding crops tend toward lower protein, high yield years usually result in low protein levels and higher discounts for low protein HRSW.

Providing adequate available N when the plant requires it may be the most important management factor to enhance grain protein in hard red spring wheat. Inadequate N management is most often the reason for low protein in wheat. In a 2012 survey, Montana producers used an average of 48.3 kg N ton^{-1} production on HRSW (Jones and Olson-Rutz, 2012). In 2010, with high protein discounts, it was estimated that under-fertilization of N cost Montana spring wheat producers between $62 to $148 ha^{-1}.

To produce high grain protein, there must be enough available N to meet the requirements of both vegetative growth and grain protein. If there is enough available N uptake to satisfy growth and yield requirements, extra N taken up by wheat is used for increasing grain protein (Jenner, 1991). Grain from wheat stressed by drought or elevated temperatures during grain fill frequently has higher protein, although certain crop and fertilizer management practices can increase protein without sacrificing yield, regardless of weather conditions (Jones and Olson-Rutz, 2012). For HRSW, a small amount of N is required in the first two to four weeks after seeding; however, most of the remaining N is required over the next 30 d (Franzen, 2011). Increasing yield from optimal cultural practices or correcting nutrient shortages can reduce protein if no additional N is provided (Brown et al., 2005).

Many factors can influence variability of grain protein content, such as variety, fertilizer rate, application timing, yield potential, fertilizer application method, and plant N status. Applying the proper rate of N fertilizer, choosing the correct timing of application, the source of N and consideration of environmental conditions, particularly early season rainfall are key decision considerations for wheat growers. Currently, N fertilizer recommendations for most crops, including HRSW, are based on region, farmer tillage system, consideration of the amount of NO_3^- to a depth of 60 cm in the soil, historical productivity of the field or a neighboring field, and previous crop N credit (Franzen, 2010).

Nitrification Inhibitors

Certain N additives provide growers with options that help extend the availability of N to crops. Some N additives have the potential to increase crop yields by delaying the transformation processes of N, thereby better synchronizing N availability with growth stage and development and peak crop N demand (Franzen, 2017). Urease and/or nitrification inhibitors are examples of additives that can reduce N losses and increase N use efficiency in fertilized fields, as well as the use of urea with poly-coatings that result in a physical barrier to N transformations.

Nitrification is a two-step bacterial process in which NH_4^+ is converted to nitrite (NO_2^-), mediated by the bacteria in the genus *Nitrosomonas spp* and then to NO_3^- by bacteria in the genus *Nitrobacter spp*, which are both, aerobic bacteria found in soil. Nitrification proceeds rapidly in warm, moist, well-aerated soils (Wiederholt and Johnson, 2005), but will not occur in saturated soils due to lack of adequate oxygen (Franzen, 2017).

Nitrate is a negatively charged ion that is not attracted to soil particles in most temperate climate soils with clays having a cation exchange capacity (CEC) or soil organic matter which is likewise negatively charged. Ammonium, however, is retained by soil clay and organic matter due to its positive charge (NH_4^+). Therefore, NO_3^- can leach below the crop rooting zone when soil water moves deeper in the soil. Ammonium may move deeper in the soil if the CEC is low (<10) and rainfall is high. Nitrapyrin (2-chloro-6-[trichloromethyl] pyridine) is the active ingredient in the N-stabilizing product Instinct and has a very selective effect on *Nitrosomonas spp.* to suppress or inhibit their activity in the soil through its mode of action as a bacteriocide, keeping N in the stable NH_4^+ form longer. This can help prevent or delay leaching and denitrification of NO_3^- and increase the efficiency of N applied (Trenkel, 2010). Denitrification is a process by which bacteria convert NO_3^- to N_2, a gaseous form of N that is not bioavailable, and is lost to the atmosphere. Denitrifying bacteria use NO_3-N instead of oxygen in the metabolic processes. Denitrification increases in waterlogged soils with ample organic matter to provide energy for the bacteria. This can happen rapidly when soils are warm and are saturated for two or more days (Lamb, 2014).

Dicyandiamide (DCD) is another nitrification inhibitor containing about 67% N. In the soil, DCD has a bacteriostatic effect on *Nitrosomonas spp.*, inhibiting the bacteria for a period of time (Trenkel, 2010). Although DCD has been shown that it can be used as a nitrification inhibitor, results have indicated it tends to have a shorter effective activity period than nitrapyrin (Bronson et al., 1989). A review on DCD conducted in North Central states by Malzer et al. (1989) concluded that DCD was similar in nitrification inhibition when compared to nitrapyrin, however, yield results comparing DCD treated fertilizer and non-treated fertilizer were inconsistent (Malzer et al., 1989). It can be concluded that yield response to DCD is more likely to be observed in areas prone to N loss through nitrification and subsequent leaching and denitrification, however, there may still be environmental benefits from the use of nitrification inhibitors even in the absence of a yield response (Trenkel 2010).

Nitrogen applied in the fall with a nitrification inhibitor may prevent or reduce nitrate losses following spring rains, as heavy rains increase leaching and denitrification. Although the movement of NO_3^- with soil water cannot be completely prevented, inhibiting the rate of transformation of N to NO_3^- may reduce the quantity of N moved by water early in the season, as NH_4^+ is much more immobile due to its positive charge allowing greater plant uptake.

Urease Inhibitors

Urease inhibitors can be used to decrease the rate of ammonia (NH_3) volatilization and enhance the utilization efficiency of urea or urea-ammonium nitrate (UAN) solutions applied to the soil surface (Brouder, 1996). Studies have shown that surface-applied urea or fertilizers containing urea have the potential for significant NH_3 volatilization and that the presence of the urease inhibitor N-(n-butyl) thiophosphoric acid triamide (NBPT) when applied with the urea fertilizer significantly reduced soil NH_3 volatilization (San Francisco et al., 2011). This product is sold under the trade name Agrotain (Koch Agronomic Services, Wichita, KS.) and other products. Agrotain and products which contain a similar (26.9% NBPT) concentration of NBPT and a similar rate of active ingredient per ton of urea are effective as a urease inhibitor and have consistently decreased ammonia volatilization in replicated studies when mixed with urea or UAN solutions (Franzen, 2017).

When urease comes into contact with a urea molecule, the urea is drawn to the active site and transformed into CO_2 and free NH_3, where volatilization is likely if the NH_3 is released near the surface (Rochette et al., 2013 (Journal Environmental Quality); Franzen, 2017). The mechanism of NBPT is to lock onto the urease-enzyme binding site, thus preventing interaction between the enzyme and urea, and delaying the transformation of urea to CO_2 and free NH_3 for 7 to 14 days; usually about 10 days under normal spring planting conditions. The use of NBPT slows down the rate at which urea hydrolyzes in the soil, thus avoiding or reducing volatilization losses of NH_3 to the air, as well as further leaching losses of NO_3^- (Trenkel, 2010). Conditions that increase potential for NH_3 volatilization include: surface-applied urea, shallow incorporation of urea (<3 cm) (Rochette et al., 2013) large amounts of surface residue, high soil pH, low cation-capacity soils, moist to drying soils, high temperatures, and no rainfall after application (Franzen, 2017). In addition to delaying NH_3 volatilization from surface-applied urea, NBPT may also be used to protect seed from injury when applying urea at planting, although given the variability of seedling germination times, agronomists are reluctant to recommend this as a standard practice (Grant, 2008).

A study at Purdue University found that NBPT generally increased crop yields with broadcast treatments and effectiveness was maximized when UAN (urea ammonium nitrate solutions) were broadcast and left on the soil surface. The UAN treatment with NBPT, applied with pelleted urea, also responded favorably to NBPT which decreased the rate of NH_3 volatilization (Brouder, 1996). Although urease inhibitors are effective in limiting NH_3 volatilization, they do not eliminate it. The effectiveness of urease inhibitors is dependent on many factors such as rainfall following application, method of application, timing, and soil characteristics (Franzen, 2017).

Nitrification and Urease Inhibitors

Agrotain Plus contains the nitrification inhibitor DCD, plus the urease inhibitor NBPT. This product is a water soluble, dry flowable additive and is designed for mixing with UAN solutions and urea solutions to reduce volatilization losses of ammonia due to urease as well as N losses from denitrification and leaching.

Controlled-Release Nitrogen Fertilizer

In addition to nitrification and urease inhibitors, controlled-release fertilizers have been proposed as tools to improve fertilizer-use efficiency in the U.S. north-central region by reducing N loss through leaching and reducing gas emissions, especially in high-moisture conditions.

Environmentally Smart Nitrogen (ESN) (Agrium Inc., Calgary, Canada), is a polymer-coated urea (PCU), which physically separates urea from soil until the urea diffuses through the polymer coating as a result of the combined effects of temperature and soil moisture. The PCU delays the exposure of the coated urea to soil urease enzyme, thereby delaying risk of ammonia volatilization, and delays transformation of ammonia produced by urease activity to NO_3^-. From this PCU, N availability for plant uptake is delayed compared to uncoated conventional urea after application, but it is also available to the plant significantly longer than rapidly available N fertilizers such as UAN or pelleted urea (AAPFCO, 1995), particularly when urea is applied to the soil surface, or early season rainfall is high. Through gradual nutrient release, losses of N through ammonia volatilization are reduced, as are losses of NO_3^-, and the subsequent risk of environmental degradation due to leaching or loss of nitrous oxide due to denitrification (Trenkel, 2010).

Research by Idaho Univeristy, (Brown, 2009) compared broadcast PCU to non-coated urea at different N application rates for evaluation of preplant effectiveness on irrigated HRSW. Yields at the 202 kg N ha^{-1} application rate increased as the ratio of PCU to urea increased in a preplant application, and grain protein concentration increased with added N. However, protein concentration did not differ for the 100% urea treatment between the 134 kg ha^{-1} and 202 kg ha^{-1} rates. Yields were higher for PCU and protein improved with PCU as the N source compared to urea at the highest N rate. Grain protein concentrations did not differ regardless of source when 67 kg ha^{-1} of N was applied as a late season top-dress. Total grain N removed with the harvest increased with N rate and was greater with PCU than with urea at both N rates.

While this study (Brown, 2009) provided data supporting PCU over urea alone in irrigated HRSW, more research comparing PCU with other N fertilizer types, rates, and timings is needed to provide support for the use of PCU across a broad range of treatments and environments so that growers across the HRSW growing region can make informed N management decisions regarding their use, particularly in dryland environments.

Timing of Application

In certain situations, a split application of N may result in higher yield and grain protein when compared to a single application. Fall applied N leaching deeper into the soil over the winter season may boost grain protein if deep rooting activity has access to the deep N, since rooting activity during grain fill is at deeper levels where there may be more soil moisture (Jones and Olson-Rutz, 2012). However, the potential for N to leach below plant root area can also increase in environments with excess soil moisture, resulting in lower yield and lower grain protein.

Growing HRSW with high grain protein involves management practices that increase N availability later in the season. A study at the University of Montana on the value of late-season N applications to irrigated HRSW showed a consistent, positive economic benefit by boosting grain protein levels at sites across the state of Montana (Westcott et al., 1998). Net increases in crop values due to late-season N application averaged \$118 ha^{-1} at four sites in 1994, and \$16 ha^{-1} at five sites in 1995. In dryland HRSW production, late season N application requires sufficient rainfall to move the N to the plant root zone to allow optimal uptake of added N for protein, as well as reasonable yield for the crop, unless foliar N is applied early post-anthesis.

Protein increases associated with late season N can vary from year to year. When comparing preplant versus a late season split application, N management in the early season according to Wuest (1992) should target grain yield while late season N fertilizer applications should focus on enhancing protein levels. However, given the uncertainty of seasonal rainfall, application of preplant N in North Dakota for yield and protein are recommended by Franzen (2010). Timing may be an important factor in N management in years with high early season rainfall. Use of controlled-release N as well as additives such as nitrification and/or urease inhibitors may aid in greater consistency of preplant N treatments across environments.

Remote Sensor Technology as a Tool in N Management

Active-optical sensor-based technology has been used as a measurement tool to assess the health and vigor of a crop to aid in N management decisions, as well as the potential to estimate yield and protein in HRSW. Active remote optical sensors such as the GreenSeeker (Trimble, Sunnyvale, CA), include light sources and detectors using visible red (R) and near infrared (NIR) light. This light is emitted from the sensor to the canopy and the amount and type of light that is reflected from the plant is measured. Normalized difference vegetative index (NDVI) is calculated using the following equation: NDVI = (NIR – VIS) / (NIR + VIS). As the sensor passes over the crop's surface, it measures incident and reflected light from the canopy and outputs both NDVI and red to near infrared ratios (Lan et al., 2009).

The strength of the light reflected estimates biomass and is an indicator of the health and vigor of the crop. These values are used to determine NDVI and are displayed as values ranging from 0.00 to 0.99.

Field studies in South Dakota have shown the GreenSeeker to be a promising tool in predicting grain protein concentration and has the potential to benefit producers when making N management decisions (Qualm et al., 2010). However, this technology was not reliable when water stress limited crop production due to stunted vegetative growth and the resulting low yields.

A newer technology in active remote sensing is the RapidSCAN CS-45 (Holland Scientific, Lincoln, NE). The device is a self-contained active crop canopy sensor that integrates a data logger, GPS, and crop sensor. Where the GreenSeeker sensor uses an active light source with monochromatic output, RapidSCAN has an internal polychromatic light source, allowing for biomass readings in overcast or nighttime conditions, as the readings are unaffected by ambient illumination. This device incorporates three optical measurement channels and simultaneously measures crop/soil reflectance at 670 nm, 730 nm, and 780 nm.

The RapidSCAN is also capable of making height independent spectral reflectance measurements and produces RNDVI/RENDVI vegetation indexes as well as basic reflectance information. [RENDVI= (NIR - RE) / (NIR + RE), NIR= NIR reflectance, RE= reflectance in red]. Normalized difference red edge (RENDVI) uses a red edge filter to view the reflectance from the canopy of the crop. The red edge is a region in the red-NIR transition zone of vegetation reflectance spectrum and marks the boundary between absorption by chlorophyll in the red visible region and scattering due to leaf internal structure in the NIR region (Horler et al., 1983).

RESEARCH OBJECTIVES

The objectives of this experiment were to: 1) evaluate N fertilizer types, additives, rates, and timing for grain yield and protein content of HRSW. The overall goal is to determine if specific N application methods increase grain protein content while maintaining grain yield; 2) to determine if ground-based active optical sensor data can predict grain yield and/or grain protein content and be used as a tool to determine if in-season N applications will be profitable.

MATERIALS AND METHODS

General Information

Field experiments were conducted from 2015 to 2016 in North Dakota and Minnesota. In 2015, experiments were established at three locations: Casselton, ND, (latitude = 46.88^{o} N, longitude = 97.24^{o} W); Gentilly, MN, (latitude = 47.78^{o} N, longitude = 96.46^{o} W); and Stephen, MN, (latitude = 48.49^{o} N, longitude = 96.99^{o} W). The study was repeated at three different locations in 2016: Casselton, ND, near the location of the 2015, but not within the 2015 experimental site area (latitude = 46.88^{o} N, longitude = 97.24^{o} W); Red Lake Falls, MN, (latitude = 47.87^{o} N, longitude = 96.27^{o} W); and Ada, MN, (latitude = 47.34^{o} N, longitude = 96.42^{o} W).

Soil samples were collected in the fall of 2014 and 2015 to determine the levels of NO_3^-, phosphorous (P), potassium (K), pH, and organic matter in the soil at each location with the exception of Gentilly and Stephen, where soil tests were unable to be obtained in 2014 (Table 2). The previous crop in Gentilly and Stephen were sunflower (*Helianthus annuus*.) and sugar beet (*Beta vulgaris L.*), respectively. Five random core samples were collected and combined from the proposed experimental area for analysis at each location.

Table 1. Soil series, soil texture, soil taxonomy, and slope at Casselton, ND, and Stephen, Gentilly, Ada, and Red Lake Falls, MN (2015-2016).

Location	Year	Soil Series†	Soil Texture†	Soil Taxonomy‡	Slope
					%
Casselton	2015-2016	Kindred	Silty Clay Loam	Fine-silty, mixed, superactive, frigid Typic Endoaquolls	0-2
		Bearden	Silty Clay Loam	Fine-silty, mixed, superactive, frigid Aeric Calciaquolls	0-3
Stephen	2015	Colvin	Silty Clay Loam	Fine-silty, mixed, superactive, frigid Typic Calciaquolls	0-2
Gentilly	2015	Huot	Fine Sandy Loam	Fine-sandy loam, mixed, frigid Aquic Calciaquolls	0-3
Ada	2016	Ulen	Fine Sandy Loam	Sandy, mixed, frigid Aeric Calciaquolls	0-3
Red Lake Falls	2016	Wheatville	Very Fine Sandy Loam	Coarse-silty over clayey, mixed over smectitic, superactive, frigid Aeric Calciaquolls	0-3

† Soil data obtained from Web Soil Survey (USDA-NRCS, 2016).
‡ Soil taxonomy listed on individual lines based on hyphenated soil series name.

Table 2. Previous crop, available N, P, K, pH, and organic matter levels by sampling depth at Casselton, ND, Gentilly, Stephen, Ada, and Red Lake Falls, MN (2014 and 2015).

Location	PC†	Depth	NO_3^-N	P	K	pH	OM†
Fall 2014		cm	kg ha^{-1}	ppm	ppm		%
Casselton	wheat	0-31	25	7	600	7.7	3.1
		31-61	13	6	400	8.1	1.9
Gentilly	sunflower	-	-	-	-	-	-
		-	-	-	-	-	-
Stephen	sugar beet	-	-	-	-	-	-
		-	-	-	-	-	-
Fall 2015							
Casselton	wheat	0-16	10	17	285	7.7	4.0
		16-61	27	8	170	8.0	2.0
Ada	soybean‡	0-16	7	4	26	8.2	2.2
		16-61	2	3	0	8.5	0.9
Red Lake Falls	soybean	0-16	29	15	70	7.3	3.6
		16-61	18	6	40	8	1.6

†PC = Previous crop; OM = Organic matter.
‡*Glycine max* L. Mezz.

Treatments and Experimental Design

The experimental design at each location was a randomized complete block with 24 treatments and 4 replicates with a non-balanced factorial combination of N sources (PCU, urea, and UAN), and application timing (fall and spring). PCU and urea were applied at 50, 75, and 100% of optimum N. In addition to PCU and urea alone, PCU and urea blends were applied at ratios of 75:25 and 50:50 PCU to urea. Nitrapyrin was applied as an additive with urea at 75 and 100 % N rates at the spring and fall timing treatments. Treatments containing UAN were applied in the spring at Zadoks growth stage (ZGS) 14 (Zadoks et al., 1974). The 50% rate of UAN as well as UAN + NBPT/DCD was applied to a 50% rate of urea which had been applied previously at planting. Each experiment location included an untreated check and a 200% rate of optimum N, serving as an N-rich plot. The complete treatment list for all experiment locations is reported in Table 3.

Fall treatments were applied October and spring treatments were applied in April. Spring UAN treatments were applied in May at the growth stage previously indicated. Application dates for each experimental location are summarized in Table 4.

Table 3. Nitrogen fertilizer rate, timing of application, and nitrogen source treatment list for Casselton, ND, Stephen, Gentilly, Red Lake Falls and Ada, MN (2015 and 2016).

Rate†	Timing	N Source
0	Fall	None
50	Fall	PCU
75	Fall	PCU
100	Fall	PCU
50	Fall	Urea
75	Fall	Urea
100	Fall	Urea
100	Fall	PCU:Urea§
100	Fall	PCU:Urea‖
75	Fall	Urea + Nitrapyrin
100	Fall	Urea + Nitrapyrin
50	Spring	PCU
75	Spring	PCU
100	Spring	PCU
50	Spring	Urea
75	Spring	Urea
100	Spring	Urea
100	Spring	PCU:Urea‡
100	Spring	PCU:Urea§
75	Spring	Urea + Nitrapyrin
100	Spring	Urea + Nitrapyrin
100	Spring	Urea:UAN¶
100	Spring	Urea:UAN + DCD/NBPT#
200	Spring	Urea

† % optimum N rates were calculated using the North Dakota Wheat Nitrogen Calculator (Franzen, 2009).
‡ 50% of N applied as PCU: 50% of N applied as urea.
§ 75% of N applied as PCU: 25% of N applied as PCU.
¶ 50% of N applied as urea in spring: 50% of N applied as UAN (34 kg ha^{-1}) at ZGS 14.
#DCD (dicyandiamide nitrification inhibitor)/NBPT, N-(n-butyl) thiophosphoric triamide urease inhibitor
applied at a rate of 561.8g active ingredient ha^{-1}.

Table 4. Nitrogen treatment application dates for Casselton, ND, and Stephen, Gentilly, Red Lake Falls, and Ada, MN experiment locations (2015 and 2016).

	2015			2016		
Treatment Timing	Casselton	Stephen	Gentilly	Casselton	Red Lake Falls	Ada
	---------------------------Day-------------------------------					
October†	15	16	16	9	13	13
April‡	7	11	16	9	13	13
May§	22	22	22	3	20	20

† Fall treatments applied before growing season.
‡ Spring treatments applied before planting.
§ Spring UAN (28-0-0) and UAN+NBPT, [N-(n-butyl) thiophosphoric triamide] at ZGS 14.

Planting and Plot Maintenance

The HRSW cultivar used in all experiments was 'Faller'. This cultivar was selected based on genetically high yield potential and genetically lower protein content. Characteristics of the Faller HRSW cultivar are shown in Table 5.

Table 5. Characteristics of Faller HRSW used in all experiment locations.

Cultivar	Origin‡	Year Released	Typical Height	Days to Head	Protein§	Yield
			cm	d	g kg^{-1}	kg ha^{-1}
Faller	ND	2007	89	65	137	4808

†Based on a three-year average (2014-2016).
‡Refers to agent or developer: ND= North Dakota State University.
§Protein at 12% moisture.

The optimum N rate in 2015 was set using the following formula, NRec = [(2.5) x YG] - STN (0-61cm) - NPC. The following values and abbreviations are used in this equation: 2.5 = lbs. of N; YG = yield goal (kg ha^{-1}); STN = nitrate-nitrogen (NO_3^- N) measured to a depth of 61cm (kg ha^{-1}); NPC = amount of N supplied by the previous crop (kg ha^{-1}). Soil tests were not conducted at Gentilly and Stephen locations in 2015 and values for optimum N were estimated at 101 kg ha^{-1} for both locations.

Optimum N rates for 2016 treatments were calculated using the North Dakota Wheat Nitrogen Calculator (Franzen, 2009) for more precise N rates for each environment. The N calculator produces an N recommendation based on location, historical productivity, amount of nitrates and organic matter in the soil, tillage method, and previous crop credits, as well as the cost of N and the value of the harvested grain. The final N recommendation from the calculator is the suggested optimal rate. Growers may choose to apply 34 kg N ha^{-1} more or less than the calculated N rates for reasons such as: protein traits of a variety, special soil conditions, application techniques that may not be efficient, or past experiences from the specific field that may influence N uptake and efficiency (Franzen, 2009).

Experimental units at Casselton in both 2015 and 2016 were 1.5 m wide by 5.5 m long. The dimensions of each experimental unit at the Minnesota locations were 1.5 m wide by 5.9 m long. The amount of product required for each environment was calculated based on plot area, divided by 1000 m^{-2}, multiplied by the desired N ha^{-1}, and divided by the percent N in the respective N source for the weight of product needed per plot. For treatments containing nitrapyrin, the additive was applied to the urea at 561.8 g active ingredient ha^{-1} just prior to broadcasting onto field and thoroughly mixed to ensure even coverage of urea with the product.

Once soil temperatures at a 4-inch depth dropped below 10 °C from 6 to 8AM, fall granular fertilizer treatments were hand broadcast over the entire plot and incorporated into the soil within an hour after application with a cultivator. Spring treatments were applied and incorporated in the same manner as the fall treatments the date of planting. For treatments containing UAN, 34 kg h^{-1} of N was applied at ZGS 14 with a CO_2 pressurized backpack sprayer and streamer bar boom with a pressure of 207 kPa and a consistent speed of 4.8 km ha^{-1}. The boom was kept approximately 46 cm above the canopy and offset from the crop rows to prevent direct contact with the plant while streaming UAN. For the treatment requiring a urease inhibitor, DCD/NBPT was added to the UAN solution at the label recommended rate of 1.5 ml kg^{-1} of applied N.

All trials were planted using a 3P605NT (6-row) grain drill (Great Plains Mfg. Inc., Salina, KS) with 18 cm row spacing, at a rate of 3.95 million seeds ha^{-1}. A uniform seed bed was prepared prior to planting and fertilizer was incorporated to a depth of 5 cm using a field cultivator. Borders between plots were 0.3 m and alleys between reps were cut mid-season at a width of 0.8 m. Plots were trimmed from each end during the growing season using a soil rotovator to the lengths previously defined to maintain an alley. Planting and harvest dates of experiment locations are reported in Table 6.

Table 6. Planting and harvest date of experiment locations (2015 and 2016).

Year	Location	Planting	Harvest
		---------Date--------	
2015	Casselton	7 Apr.	12 Aug.
	Stephen	16 Apr.	14 Aug.
	Gentilly	16 Apr.	14 Aug.
2016	Casselton	13 Apr.	1 Aug.
	Red Lake Falls	13 Apr.	3 Aug.
	Ada	14 Apr.	30 July

Predictive Measurements

Normalized Difference Vegetation Index measurements were taken in 2015 and 2016 using an active optical ground-based sensor (GreenSeeker). The NDVI measurements were obtained with the GreenSeeker twice (ZGS 16 and 31) at experiment locations in 2015 and 2016, while RapidSCAN CS-45 readings were obtained only once at ZGS 50 in 2016. The RapidSCAN readings were taken at a later growth stage due to a delay in acquiring the device at an earlier date. Both devices were held approximately 50 cm above the canopy while walking through the plots at a constant speed of approximately 1.3 m sec^{-1}.

Harvest and Data Collection Equipment

Experimental units were harvested using a Wintersteiger Classic plot combine (Wintersteiger Ag, Ried, Austria). A HarvestMaster Classic Grain Gage (Juniper Systems, Logan, UT) measured grain yield, moisture, and test weight on the combine. A 500 g sample of grain was retained from each experimental unit for moisture, test weight, and protein analysis. The sample was cleaned using a Clipper Office Tester and Cleaner (Seedburo Equipment Co., Chicago, IL). Samples were processed for moisture and test weight using a GAC 2100 moisture tester (Dickey-John Corp., Minneapolis MN). Grain protein was analyzed using a DA 7250 NIR analyzer (Perten Instruments, Hägersten, Sweden).

Statistical Analysis

Data was subjected to statistical analysis using SAS 9.4 (SAS Institute, Cary, NC). The data code was written using PROC Mixed. Location, year, and replicates were considered random variables while N treatments (application time, fertilizer source, and application rate) were considered fixed variables. All fixed effect interactions were considered fixed, while any interactions containing a random term were considered random.

Each location for 2015 and 2016 was analyzed separately and then all locations were combined and analyzed for both years of the study. Single degree-of-freedom non-orthogonal contrasts were used to evaluate the relationship between N rates, timing, fertilizer source, and grain protein and yield since the treatment structure was not balanced. Means were separated using Fisher's protected least significant difference (LSD) at the 95% level of confidence (α=0.05).

Contrasts made include PCU vs. urea averaged over all rates and both fall and spring dates. When comparing fall versus spring applications overall, the contrast included all similar N treatments, so therefore, did not include the UAN treatments that were applied only in spring. Since nitrapyrin was only applied with 75 and 100 percent rates of urea, the contrast compared the urea and nitrapyrin treatments to urea alone at the 75 and 100 percent rates and in both fall and spring.

Linear regression was used to determine the relationship between plant-based predictors, grain protein content, and grain yield of the harvested grain. Correlation coefficients between grain protein and observed variables were calculated using the PROC CORR in SAS.

Economic Analysis

Partial profits of each N treatment were calculated by subtracting total application cost from the price of grain after the protein premium and discount. The total application cost included the price of N product and an assumed application cost of $14.82 per hectare and $29.64 when two applications were made. The cost of spring applied N sources were the actual price of that product in the spring ($520, $390, $245 per ton for ESN, urea and UAN, respectively), and fall applied N was the cost of the product in the fall ($470, $345 per ton for ESN and urea, respectively). All grain protein premiums and discounts were obtained from CHS Northland Grain based on current market prices as of March 2016, at 4 cents per fifth of a percent above 14% protein and 6 cents per fifth of a discount below 14 percent. The market price of wheat at 14% protein was set at $4.60 per bushel.

RESULTS AND DISCUSSION

Weather Information

Variability in weather conditions can affect grain protein concentration and grain yield. Temperature and rainfall are important components of N dissolution from PCU and subsequent transformation and losses from the soil and rhizosphere. In both years, Casselton, ND, experienced above average rainfall in April and below average rainfall in June and August (Table 7). In 2015, Stephen, MN, had above normal rainfall in both May and July with below normal rainfall in June. Gentilly, MN, received above average rainfall in May and remained significantly drier than normal throughout the rest of the growing season. In 2016, Ada, MN, location experienced below average rainfall earlier in the season and above average rainfall through July and August. Red Lake Falls, MN, rainfall amounts were consistent with normal for that area throughout the growing season, except for June which was slightly drier than normal. Wheat response to N treatments may have been impacted by below or above average rainfall through growing seasons at the experiment locations.

While variability in rainfall was in observed both years, the monthly mean air temperature at all locations remained near normal in both 2015 and 2016, except for Casselton, which was 2 °C warmer than normal in May 2016. Table 8 shows the monthly mean temperatures for each location during the study period.

Table 7. Average mean rainfall for the months of planting to harvest at 2015 and 2016 experiment environments, along with normal (1990-2016) †.

	Casselton‡			Stephen		Gentilly§		Ada		Red Lake Falls¶	
Month	2015	2016	Normal	2015	Normal	2015	Normal	2016	Normal	2016	Normal
	---mm---										

April	20	43	37	14	26	16	31	41	36	40	32
May	149	82	78	128	70	108	74	51	82	74	76
June	110	38	100	70	94	68	97	65	114	98	114
July	88	88	89	153	70	54	76	156	93	81	85
August	36	26	67	82	77	46	84	173	70	110	97

† Information collected from NDAWN, 2016.

‡ Weather information collected from the Prosper, MN weather station (latitude = 47.00º N, longitude = -97.12º W).

§ Weather information collected from the Eldred, MN weather station (latitude = 47.69° N, longitude = -96.82°W).

¶ Weather information collected from the Mavie, MN weather station (latitude = 48.12 N°, longitude = -95.97° W).

Table 8. Average mean air temperature for the months of planting to harvest at 2015 and 2016 experiment environments, along with normal (1990-2016) †.

	Casselton‡			Stephen		Gentilly§		Ada		Red Lake Falls¶	
Month	2015	2016	Normal	2015	Normal	2015	Normal	2016	Normal	2016	Normal
						°C					
April	8	6	6	6	5	7	6	5	6	6	6
May	12	15	13	12	12	12	13	15	13	12	13
June	19	19	19	18	18	18	18	19	19	18	18
July	21	21	21	21	20	21	21	21	21	20	20
August	19	21	20	19	19	20	20	20	20	18	20

† Information collected from NDAWN, 2016.

‡ Weather information collected from the Prosper, MN weather station (latitude = 47.00º N, longitude = -97.12º W).

§ Weather information collected from the Eldred, MN weather station (latitude = 47.69° N, longitude = -96.82°W).

¶ Weather information collected from the Mavie, MN weather station (latitude = 48.12 N°, longitude = -95.97° W).

Contrasts

Means and single degree-of-freedom linear contrasts for grain protein concentration and grain yield for each individual location, as well as 2015-2016 environments combined, are reported in Tables 9-15. Significant differences were found between N treatment and grain protein concentration. At all locations, N treatment affected grain protein in 2015 and 2016.

Grain protein at the 2016 Casselton location was relatively high for all treatments, most likely due to unusually high rates of mineralization and limited N losses, as indicated by high check yields, therefore N was not limiting at this location. However, when comparing all N treatments, protein was improved with spring applications compared to fall applications. The highest proteins from this location came from the 50:50 PCU urea blends with a protein of 145 g kg^{-1} in both fall and spring treatments (Table 14). Treatments that resulted in the highest protein concentration across locations were spring applied PCU at the 100% rate optimum N and spring applied blend of 50% PCU and 50% urea (Table 9). The average protein concentration for these treatments 132g kg^{-1}, respectively. Spring applied PCU at the 100% optimum N rate increased protein compared to spring applied urea at the same rate by 0. 5 g kg^{-1}. However, the spring 50:50 blend of PCU and urea protein was the same at 132 g kg^{-1} (Table 9).

In all but two environments, (Gentilly, 2015 and Casselton, 2016) yield was affected by N treatment. The untreated checks yielded significantly lower than any other fertilizer treatment, indicating that N was not limiting in these environments.

Timing

Across all environments, spring treatments had significantly higher grain protein and grain yield compared to fall applied treatments. Fall vs. spring applications did not affect yield when comparing PCU to urea. However, N treatments applied in the spring had better yield response than fall applied treatments. In 2015, the Gentilly site had significantly higher protein response to spring applied N treatments compared to fall (Table 11). Spring applied PCU compared to fall PCU had significantly higher protein where spring applied PCU improved protein by 1.4% at the 100% rate, 1% at the 75% rate, and 1.2% at the 50% rate compared to fall applied PCU at the same rates (Table 11).

Nitrogen Source

The PCU and PCU:urea blend produced significantly higher grain protein when compared to urea alone for both the spring and fall application timings. Furthermore, PCU applied in the spring improved protein compared its fall application, without a significant increase or decrease in yield. Fall vs. spring applications did not affect yield when comparing PCU to urea, however N treatments applied in the spring had better yield response than fall applied treatments (Table 9). PCU/urea blends improved protein content in both fall and spring applications compared to PCU or urea alone when averaged over rates (Table 9). The Stephen location had significantly higher protein when comparing PCU to urea at all rates and both spring and fall applications. The 50:50 PCU and urea blend treatment had the highest protein at 155 g kg^{-1} (Table 12). PCU improved protein when compared to urea applied in the spring alone at Casselton in 2015 (Table 10). When applied in the spring at the 75% rate, the PCU treatment improved protein by 1.1% compared to spring applied urea at the same rate (Table 10). When comparing PCU applied fall and spring, the spring applications improved protein by 1% at the 75% rate and 0.8% at the 100% rate compared to PCU applied at the same rates in the fall (Table 10).

When comparing the PCU blends in the fall and spring, there was no difference in protein between the 50:50 and 75:25 blends. Overall, the treatments with the best protein response were the spring applied PCU at the 100% rate and spring applied PCU: urea blend (50:50) with proteins measured at 135 and 134 g kg^{-1}, respectively. Overall, when comparing urea alone to PCU alone as well as PCU/urea blends, grain protein and grain yield were affected. The PCU and urea blends (50:50 and 75:25) improved protein by 0.9% compared to PCU alone at the 50 and 75% rate (Table 9).

Rate

When comparing PCU to urea by application rate, protein improved using PCU compared to the urea alone, and higher rates consistently increased protein, with the highest protein concentration observed at the 100% optimum N rate for both PCU and urea applied in the fall and the spring (Table 9). At Red Lake Falls, PCU treatments applied in spring improved both yield and protein compared to fall applied PCU, with the highest protein and yield response to the spring applied PCU at the 100% rate (Table 13).

Additives

Urea with the addition of the nitrification inhibitor (nitrapyrin) did improve protein when applied in the spring compared to urea alone, although increases were modest. In the fall, the addition of nitrapyrin to urea did not improve grain protein or yield when compared to urea alone (Table 9). With the exception of the Red Lake Falls location (Table 13), there was no significant improvement in grain protein or yield when comparing urea with UAN and urea with UAN+NBPT/DCD applied in spring. The Red Lake Falls location had a 1% increase in protein with the UAN+NBPT/DCD treatment compared to the urea and UAN alone (Table 13). This result could be due to unprotected N, and the addition of NBPT helping to keep the UAN viable until a rain.

Table 9. Treatment means and contrasts for grain protein and grain yield combined across all environments (2015 and 2016).

Source†	Timing‡	N Rate§	Grain Protein	Grain Yield
			g kg^{-1}	kg ha^{-1}
None	Check	0%	116	4094
PCU	Fall	50%	119	4885
PCU	Fall	75%	126	5328
PCU	Fall	100%	129	5359
Urea	Fall	50%	121	4929
Urea	Fall	75%	122	5233
Urea	Fall	100%	125	5208
PCU:urea blend	Fall	50%:50%	128	5427
PCU:urea blend	Fall	75%:25%	128	5639
Urea + nitrapyrin	Fall	75%	123	5148
Urea + nitrapyrin	Fall	100%	126	5420
PCU	Spring	50%	125	4997
PCU	Spring	75%	129	5457
PCU	Spring	100%	132	5663
Urea	Spring	50%	120	5189
Urea	Spring	75%	125	5290
Urea	Spring	100%	127	5444
PCU:urea blend	Spring	50%:50%	132	5412
PCU:urea blend	Spring	75%:25%	130	5434
Urea + nitrapyrin	Spring	75%	126	5434
Urea + nitrapyrin	Spring	100%	130	5620
50% Urea: 50% UAN§	Spring	100%	127	5431
50% Urea: 50% UAN + DCD/NBPT‡	Spring	100%	130	5561
Urea N-Rich Strip	Spring	200%	138	5821
CV (%)			5	8.9
LSD (0.05)			4	282
Contrast				
PCU (all dates and rates) vs. urea (all dates and rates)			**	ns
PCU linear rate (50,75,100) vs. urea linear rate (50,75,100)			**	ns
Urea alone over 75 and 100 rate vs. urea with nitrapyrin over 75 and 100 rate (both fall and spring)			ns	ns
Fall vs. spring (all similar N treatments)			**	**
UAN alone vs. UAN+DCD/NBPT			ns	ns
PCU linear rate (fall) vs. PCU linear rate (spring)			ns	ns
PCU (fall) vs. PCU (spring)			**	ns
Urea alone and PCU alone vs. urea/PCU blends			*	*
PCU alone (fall) vs. urea alone (spring)			ns	ns

*Significant at the 0.05 probability level.

**Significant at the 0.01 probability level.

† PCU, polymer-coated urea; UAN, urea ammonium nitrate (28-0-0).

‡ DCD/NBPT applied at a rate of 561.8g active ingredient ha^{-1}.

§ Applied % optimum N; UAN (34 kg ha^{-1}) applied at ZGS 14.

Table 10. Treatment means and contrasts for grain protein and grain yield at Casselton, ND (2015).

Source[†]	Timing	N Rate	Grain Protein	Yield
			g kg^{-1}	kg ha^{-1}
None	Check	0%	129	2028
PCU	Fall	50%	125	3318
PCU	Fall	75%	137	3502
PCU	Fall	100%	146	4051
Urea	Fall	50%	145	3638
Urea	Fall	75%	127	3762
Urea	Fall	100%	131	3721
PCU:urea blend	Fall	50%:50%	135	4001
PCU:urea blend	Fall	75%:25%	134	4126
Urea + nitrapyrin	Fall	75%	128	3557
Urea + nitrapyrin	Fall	100%	133	4126
PCU	Spring	50%	136	3488
PCU	Spring	75%	140	4076
PCU	Spring	100%	132	3872
Urea	Spring	50%	132	3917
Urea	Spring	75%	129	3557
Urea	Spring	100%	127	3973
PCU:urea blend	Spring	50%:50%	135	3453
PCU:urea blend	Spring	75%:25%	139	3954
Urea + nitrapyrin	Spring	75%	132	4122
Urea + nitrapyrin	Spring	100%	141	4572
50% Urea: 50% UAN[§]	Spring	100%	137	3641
50% Urea: 50% UAN + DCD/NBPT[‡]	Spring	100%	140	4263
Urea N-Rich Strip	Spring	200%	152	4619
CV (%)			8	11.3
LSD (0.05)			2	632
Contrast				
PCU (all dates and rates) vs. urea (all rates and dates)			ns	ns
PCU linear rate (50,75,100) vs. urea linear rate (50,75,100)			*	ns
Urea alone over 75 and 100 rate vs urea with nitrapyrin over 75 and 100 rate (both fall and spring)			ns	ns
Fall vs. spring (all similar N treatments)			ns	ns
UAN alone vs. UAN+DCD/NBPT			ns	ns
PCU linear rate (fall) vs. PCU linear rate (spring)			ns	ns
PCU (fall) vs. PCU (spring)			ns	ns
Urea alone and PCU alone vs. urea/PCU blends			ns	ns
PCU alone (fall) vs. urea alone (spring)			ns	ns

*Significant at the 0.05 probability level.

**Significant at the 0.01 probability level.

† PCU, polymer-coated urea; UAN, urea ammonium nitrate (28-0-0)

‡ DCD/NBPT applied at a rate of 561.8g active ingredient ha^{-1}.

§ Applied % optimum N; UAN (34 kg ha^{-1}) applied at ZGS 14.

Table 11. Treatment means and contrasts for grain protein and grain yield at Gentilly, MN (2015).

Source†	Timing	N Rate	Grain Protein	Grain Yield
			g kg^{-1}	kg ha^{-1}
None	Check	0%	134	4862
PCU	Fall	50%	132	5037
PCU	Fall	75%	134	5336
PCU	Fall	100%	134	5414
Urea	Fall	50%	131	4651
Urea	Fall	75%	128	5376
Urea	Fall	100%	136	4832
PCU:urea blend	Fall	50%:50%	141	5280
PCU:urea blend	Fall	75%:25%	143	5537
Urea + nitrapyrin	Fall	75%	139	5180
Urea + nitrapyrin	Fall	100%	132	5614
PCU	Spring	50%	144	5104
PCU	Spring	75%	143	5557
PCU	Spring	100%	148	5592
Urea	Spring	50%	127	5170
Urea	Spring	75%	135	5370
Urea	Spring	100%	142	5438
PCU:urea blend	Spring	50%:50%	141	5693
PCU:urea blend	Spring	75%:25%	149	5868
Urea + nitrapyrin	Spring	75%	137	5333
Urea + nitrapyrin	Spring	100%	147	5125
50% Urea: 50% UAN§	Spring	100%	137	5477
50% Urea: 50% UAN+DCD/NBPT‡	Spring	100%	140	5503
Urea N-Rich Strip	Spring	200%	154	5715
CV (%)			8	8.8
LSD (0.05)			20	ns
Contrast				
PCU (all dates and rates) vs urea (all dates and rates)			ns	ns
PCU linear rate (50,75,100) vs. urea linear rate (50,75,100)			ns	ns
Urea alone over 75 and 100 rate vs. urea with nitrapyrin over 75 and 100 rate (both fall and spring)			ns	ns
Fall vs. spring (all similar N treatments)			*	ns
UAN alone vs. UAN+DCD/NBPT			ns	ns
PCU linear rate (fall) vs. PCU linear rate (spring)			ns	ns
PCU (fall) vs. PCU (spring)			*	ns
Urea alone vs. PCU alone vs. urea/PCU blends			ns	ns
PCU alone (fall) vs. urea alone (spring)			ns	ns

*Significant at the 0.05 probability level.

**Significant at the 0.01 probability level.

† PCU, polymer-coated urea; UAN, urea ammonium nitrate (28-0-0)

‡ DCD/NBPT applied at a rate of 561.8g active ingredient ha^{-1}.

§ Applied % optimum N; UAN (34 kg ha^{-1}) applied at ZGS 14.

Table 12. Treatment means and contrasts for grain protein and grain yield at Stephen, MN (2015).

			Grain	
Source†	Timing	N Rate	Protein	Yield
			g kg^{-1}	kg ha^{-1}
None	Check	0%	129	3067
PCU	Fall	50%	141	4340
PCU	Fall	75%	151	4878
PCU	Fall	100%	151	4796
Urea	Fall	50%	134	4170
Urea	Fall	75%	145	4561
Urea	Fall	100%	144	4824
PCU:urea blend	Fall	50%:50%	147	4950
PCU:urea blend	Fall	75%:25%	149	4968
Urea + nitrapyrin	Fall	75%	143	4784
Urea + nitrapyrin	Fall	100%	147	4933
PCU	Spring	50%	139	4063
PCU	Spring	75%	149	4685
PCU	Spring	100%	151	4731
Urea	Spring	50%	137	4497
Urea	Spring	75%	144	4586
Urea	Spring	100%	146	4988
PCU:urea blend	Spring	50%:50%	155	4628
PCU:urea blend	Spring	75%:25%	146	4787
Urea + nitrapyrin	Spring	75%	144	4513
Urea + nitrapyrin	Spring	100%	145	5128
50% Urea: 50% UAN§	Spring	100%	146	4987
50% Urea: 50% UAN + DCD/NBPT‡	Spring	100%	146	4780
Urea N-Rich Strip	Spring	200%	163	5409
CV (%)			3	7.9
LSD (0.05)			7	572
Contrast				
PCU (all dates and rates) vs. urea (all dates and rates)			**	ns
PCU linear rate (50,75,100) vs. urea linear rate (50,75,100)			**	ns
Urea alone over 75 and 100 rate vs. urea with nitrapyrin over 75 and 100 rate (both fall and spring)			ns	ns
Fall vs. spring (all similar N treatments)			ns	ns
UAN alone vs. UAN+NBPT			ns	ns
PCU linear rate (fall) vs. PCU linear rate (spring)			ns	ns
PCU (fall) vs. PCU (spring)			ns	ns
Urea alone and PCU alone vs. urea/PCU blends			ns	ns
PCU alone (fall) vs. urea alone (spring)			**	ns

*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.
† PCU, polymer-coated urea; UAN, urea ammonium nitrate (28-0-0)
‡ DCD/NBPT applied at a rate of 561.8g active ingredient ha^{-1}.
§ Applied % optimum N; UAN (34 kg ha^{-1}) applied at ZGS 14.

Table 13. Treatment means and contrasts for grain protein and grain yield at Ada, MN (2016).

Source†	Timing	N Rate	Grain Protein	Grain Yield
			g kg^{-1}	kg ha^{-1}
None	Check	0%	117	3604
PCU	Fall	50%	119	5466
PCU	Fall	75%	119	5562
PCU	Fall	100%	127	6108
Urea	Fall	50%	118	5432
Urea	Fall	75%	124	5771
Urea	Fall	100%	125	5625
PCU:urea blend	Fall	50%:50%	128	5735
PCU:urea blend	Fall	75%:25%	128	6345
Urea + nitrapyrin	Fall	75%	123	5177
Urea + nitrapyrin	Fall	100%	129	5948
PCU	Spring	50%	122	5431
PCU	Spring	75%	129	6164
PCU	Spring	100%	135	6527
Urea	Spring	50%	121	6125
Urea	Spring	75%	125	6009
Urea	Spring	100%	130	5692
PCU:urea blend	Spring	50%:50%	134	5948
PCU:urea blend	Spring	75%:25%	133	6072
Urea + nitrapyrin	Spring	75%	129	6156
Urea + nitrapyrin	Spring	100%	130	6262
50% Urea: 50% UAN§	Spring	100%	131	5969
50% Urea: 50% UAN + DCD/ NBPT‡	Spring	100%	133	6075
Urea N-Rich Strip	Spring	200%	136	6151
CV (%)			2	8.8
LSD (0.05)			5	818
Contrast				
PCU (all dates and rates) vs. urea (all dates and rates)			ns	ns
PCU linear rate (50,75,100) vs. urea linear rate (50,75,100)			ns	ns
Urea alone over 75 and 100 rate vs. urea with nitrapyrin over 75 and 100 rates (both fall and spring)			ns	ns
Fall vs. spring (all similar N treatments)			**	**
UAN alone vs. UAN+DCD/NBPT			ns	ns
PCU linear rate (fall) vs. PCU linear rate (spring)			**	ns
PCU (fall) vs. PCU (spring)			**	ns
Urea alone vs. PCU alone vs. urea/PCU blends			**	ns
PCU (fall) vs. urea alone (spring)			**	ns

*Significant at the 0.05 probability level.

**Significant at the 0.01 probability level.

† PCU, polymer-coated urea; UAN, urea ammonium nitrate (28-0-0).

‡ DCD/NBPT applied at a rate of 561.8g active ingredient ha^{-1}.

§ Applied % optimum N; UAN (34 kg ha^{-1}) applied at ZGS 14.

Table 14. Treatment means and contrasts for grain protein and grain yield at Red Lake Falls, MN (2016).

Source†	Timing	N Rate	Grain Protein	Grain Yield
			g kg^{-1}	kg ha^{-1}
None	Check	0%	109	4885
PCU	Fall	50%	112	5818
PCU	Fall	75%	120	7057
PCU	Fall	100%	126	6492
Urea	Fall	50%	114	6237
Urea	Fall	75%	120	6757
Urea	Fall	100%	124	6886
PCU:urea blend	Fall	50%:50%	125	6856
PCU:urea blend	Fall	75%:25%	126	7229
Urea + nitrapyrin	Fall	75%	116	6617
Urea + nitrapyrin	Fall	100%	128	6828
PCU	Spring	50%	123	6423
PCU	Spring	75%	123	6751
PCU	Spring	100%	134	7537
Urea	Spring	50%	113	6036
Urea	Spring	75%	125	6867
Urea	Spring	100%	125	6827
PCU:urea blend	Spring	50%:50%	128	7108
PCU:urea blend	Spring	75%:25%	126	6916
Urea + nitrapyrin	Spring	75%	120	6521
Urea + nitrapyrin	Spring	100%	127	6959
50% Urea: 50% UAN§	Spring	100%	119	6986
50% Urea: 50% UAN + DCD/NBPT‡	Spring	100%	129	7292
Urea N-Rich Strip	Spring	200%	134	7498
CV (%)			4	5.8
LSD (0.05)			14	565
Contrast				
PCU (all dates and rates) vs. urea (all dates and rates)			ns	ns
PCU linear rate (50,75,100) vs. urea linear rate (50,75,100)			ns	ns
Urea alone over 75 and 100 rate vs. urea with nitrapyrin over 75 and 100 rate (both fall and spring)			ns	ns
Fall vs. spring (all similar N treatments)			**	ns
UAN vs. UAN+DCD/NBPT			*	ns
PCU linear rate (fall) vs. PCU linear rate (spring)			ns	ns
PCU (fall) vs. PCU (spring)			**	*
Urea alone and PCU alone vs. urea/PCU blends			ns	*
PCU alone (fall) vs. urea alone (spring)			ns	ns

*Significant at the 0.05 probability level.

**Significant at the 0.01 probability level.

† PCU, polymer-coated urea; UAN, urea ammonium nitrate (28-0-0).

‡ DCD/NBPT applied at a rate of 561.8g active ingredient ha^{-1}.

§ Applied % optimum N; UAN (34 kg ha^{-1}) applied at ZGS 14.

Table 15. Treatment means and contrasts for grain protein and grain yield at Casselton, ND (2016).

			Grain	
Source†	Timing	N Rate	Protein	Yield
			g kg^{-1}	kg ha^{-1}
None	Check	0%	123	4770
PCU	Fall	50%	133	5334
PCU	Fall	75%	140	5501
PCU	Fall	100%	143	5293
Urea	Fall	50%	134	5448
Urea	Fall	75%	136	5170
Urea	Fall	100%	139	5361
PCU:urea blend	Fall	50%:50%	145	5643
PCU:urea blend	Fall	75%:25%	143	5540
Urea + nitrapyrin	Fall	75%	136	5575
Urea + nitrapyrin	Fall	100%	134	5060
PCU	Spring	50%	140	5583
PCU	Spring	75%	139	5471
PCU	Spring	100%	143	5567
Urea	Spring	50%	135	5388
Urea	Spring	75%	143	5302
Urea	Spring	100%	142	5764
PCU:urea blend	Spring	50%:50%	145	5143
PCU:urea blend	Spring	75%:25%	142	5552
Urea + nitrapyrin	Spring	75%	144	5811
Urea + nitrapyrin	Spring	100%	142	5707
50% Urea: 50% UAN§	Spring	100%	142	5451
50% Urea: 50% UAN + DCD/NBPT‡	Spring	100%	143	5376
Urea N-Rich Strip	Spring	200%	146	5450
CV (%)			4	5.6
LSD (0.05)			9	469
Contrast				
PCU (all dates and rates) vs. urea (all dates and rates)			ns	ns
PCU linear rate (50,75,100) vs. urea linear rate (50,75,100)			ns	ns
Urea alone over 75 and 100 rate vs. urea with nitrapyrin over 75 and 100 rate (both fall and spring)			ns	ns
Fall vs. spring (all similar N treatments)			*	ns
UAN alone vs. UAN+DCD/NBPT			ns	ns
PCU linear rate (fall) vs. PCU linear rate (spring)			ns	ns
PCU (fall) vs. PCU (spring)			ns	ns
Urea alone vs. PCU alone vs. urea/PCU blends			ns	ns
PCU alone (fall) vs. urea alone (spring)			ns	ns

*Significant at the 0.05 probability level.

**Significant at the 0.01 probability level.

† PCU, polymer-coated urea; UAN, urea ammonium nitrate (28-0-0).

‡ DCD/NBPT applied at a rate of 561.8g active ingredient ha^{-1}.

§ Applied % optimum N; UAN (34 kg ha^{-1}) applied at ZGS 14.

Economic Analysis

Adding nitrogen fertilizers, regardless of rate and type, improved partial profit (Table 15). Somewhat surprisingly the highest partial profit was achieved with the N rich treatment, largely due to the value of the extra protein resulting from the extra N. The next highest partial profit was achieved with the 100% rate PCU applied in the spring with a return of $761 per hectare. Spring applications whether ESN or urea alone, tended to produce more profit when compared to fall applications. The blends of ESN and urea tended to do better than ESN or urea alone at the same rate of N in the fall, but not in the spring. Averaged over all rates, PCU was slightly more profitable than urea when applied in the spring. In the fall, PCU:urea blends were more profitable than PCU or urea alone, at the 100% rate. This could be due to having both the faster dissolved N from urea, as well as the slower-released N from the PCU through the season. Adding nitrapyrin did not significantly improve profits when applied in the fall with urea. However, when applied with urea in the spring partial profits were consistently higher when compared to urea alone. Overall, the spring applications were more profitable, with the exception of the 75%:25% PCU:urea blend in the fall, with a partial profit of $754.

Table 16. Effect of rate, timing and source of N on partial profits of spring wheat, averaged across all environments (2015 and 2016).

Source[†]	Timing	Rate	Partial Profits
		%	$/ha
None	Check	0%	584
PCU	Fall	50%	638
PCU	Fall	75%	714
PCU	Fall	100%	707
Urea	Fall	50%	673
Urea	Fall	75%	703
Urea	Fall	100%	696
PCU:urea blend	Fall	50%:50%	730
PCU:urea blend	Fall	75%:25%	754
Urea + nitrapyrin	Fall	75%	667
Urea + nitrapyrin	Fall	100%	705
PCU	Spring	50%	681
PCU	Spring	75%	743
PCU	Spring	100%	761
Urea	Spring	50%	701
Urea	Spring	75%	721
Urea	Spring	100%	733
PCU:urea blend	Spring	50%:50%	739
PCU:urea blend	Spring	75%:25%	722
Urea + nitrapyrin	Spring	75%	720
Urea + nitrapyrin	Spring	100%	750
50% Urea: 50% UAN[§]	Spring	100%	715
50% Urea: 50% UAN + DCD/NBPT[‡]	Spring	100%	744
Urea N-Rich Strip	Spring	200%	768

† PCU, polymer-coated urea; UAN, urea ammonium nitrate (28-0-0).
‡ DCD/NBPT applied at a rate of 561.8g active ingredient ha^{-1}.
§ Applied % optimum N; UAN (34 kg ha^{-1}) applied at ZGS 14.

NDVI/RENDVI

Means for NDVI and RENDVI, grain protein, and yield can be observed in Table 16. The lowest NDVI and RENDVI values were observed in the untreated checks and were also where the lowest grain yield and protein were observed. There was significance by N treatment observed for GreenSeeker readings taken at both growth stages. The highest RENDVI reading was observed in the N rich treatment where grain protein and yield were highest.

Linear regression from sensor readings showed a strong relationship between grain yield and grain protein across all environments and years (Figure 1). The R^2 was 0.73 and as grain yield increased so did grain protein. For the cultivar Faller, there was not an inverse relationship between yield and protein, likely from the higher yield and protein levels arising due to elevated levels of available N from treatments or mineralization in a particular environment.

At ZGS 16, the earliest measurement of NDVI in this research, the coefficient of determination was lowest among all variables for grain protein, with an R^2 value of 0.19 (Figure 2). The slope of the line for grain protein increased as normalized NDVI increased. Grain yield had a much higher coefficient of determination of 0.50 at ZGS 16, with a slope that also increased as normalized NDVI increased (Figure 3). The check treatment of zero nitrogen makes up the lowest grain protein and NDVI data point. The coefficient of determination was highest at ZGS 31 for grain protein and grain yield with R^2 values at 0.52 and 0.88, respectively (Figures 4 and 5).

Table 17. Means for NDVI, RENDVI, grain protein, and yield at harvest, averaged across all environments (2015 and 2016).

Source*	Timing	N Rate†	GS1‡	GS2§	RapidSCAN	Grain Protein	Grain Yield
			NDVI¶	NDVI	RENDVI±	g kg^{-1}	kg ha^{-1}
None	Check	0%	0.46	0.74	7634	116	4094
PCU	Fall	50%	0.49	0.80	7986	119	4885
PCU	Fall	75%	0.51	0.82	8053	126	5328
PCU	Fall	100%	0.48	0.82	8130	129	5359
Urea	Fall	50%	0.48	0.80	7985	121	4929
Urea	Fall	75%	0.51	0.82	8036	122	5233
Urea	Fall	100%	0.50	0.81	8051	125	5208
PCU:urea blend	Fall	50%:50%	0.51	0.82	8081	128	5639
PCU:urea blend	Fall	75%:25%	0.53	0.83	8158	128	5427
Urea + nitrapyrin	Fall	75%	0.49	0.81	7999	123	5148
Urea + nitrapyrin	Fall	100%	0.52	0.83	8068	126	5420
PCU	Spring	50%	0.47	0.79	7941	125	4997
PCU	Spring	75%	0.50	0.82	8013	129	5457
PCU	Spring	100%	0.51	0.83	8183	132	5663
Urea	Spring	50%	0.50	0.82	8068	120	5189
Urea	Spring	75%	0.50	0.82	8155	125	5290
Urea	Spring	100%	0.51	0.83	8140	127	5444
PCU:urea blend	Spring	50%:50%	0.50	0.83	8091	132	5412
PCU:urea blend	Spring	75%:25%	0.52	0.83	8098	130	5434
Urea + nitrapyrin	Spring	75%	0.52	0.84	8140	126	5434
Urea + nitrapyrin	Spring	100%	0.51	0.84	8150	130	5620
50% Urea: 50% UAN†	Spring	100%	0.51	0.83	8126	127	5431
50% Urea: 50% UAN +DCD/ NBPT**	Spring	100%	0.50	0.83	8178	130	5561
Urea N-Rich Strip	Spring	200%	0.50	0.84	8207	138	5821
CV (%)			10.5	4.2	2	5	8.9
LSD (0.05)			0.03	0.02	108	4	282

* PCU, polymer-coated urea; UAN, urea ammonium nitrate (28-0-0).
**DCD/NBPT applied at a rate of 561.8g active ingredient ha^{-1}.
†Applied % optimum N; UAN (34 kg ha^{-1}) applied at ZGS 14.
‡GS1, GreenSeeker reading taken at ZGS 16.
§GS2, GreenSeeker reading taken at ZGS 31.
¶NDVI, normalized difference vegetative index; RENDVI, normalized difference red edge taken at ZGS 50.

The RENDVI readings were taken later in the season at ZGS 50, and those values also had high coefficient of determination for grain protein with an R^2 value of 0.54 and grain yield, which had an R^2 value of 0.85 (Figures 6 and 7).

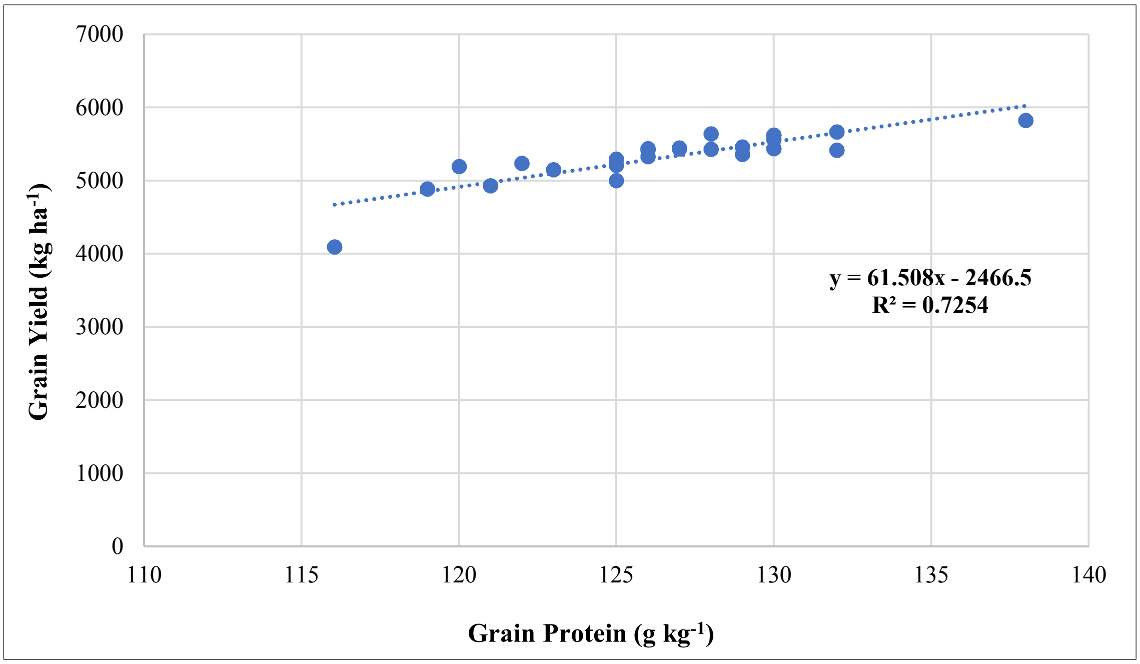

Figure 1. Linear regression of grain yield and grain protein content across all environments (2015-2016).

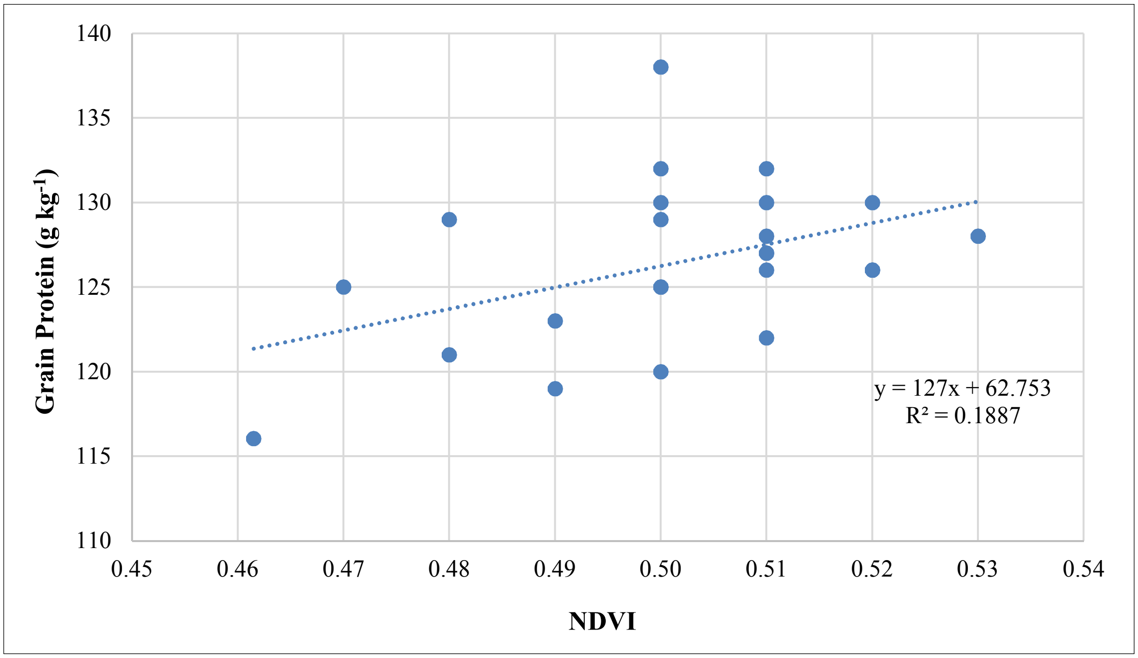

Figure 2. Linear regression of grain protein content (response variable) on NDVI values (predictor) collected at ZGS 16 across all environments (2015-2016).

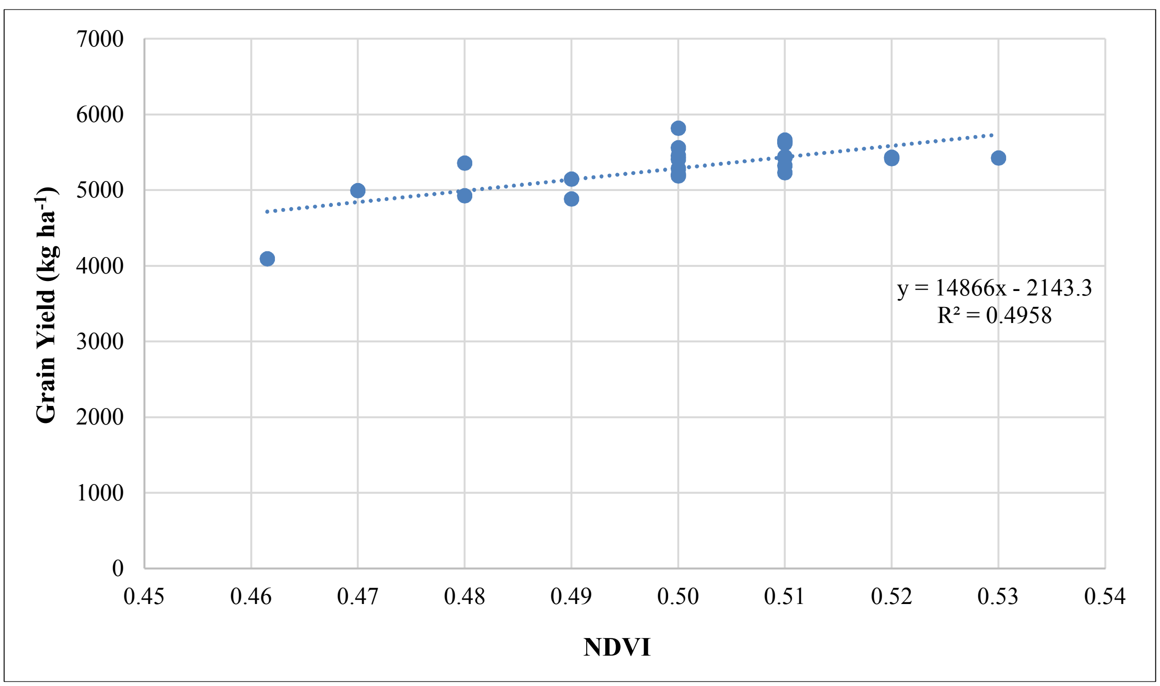

Figure 3. Linear regression of grain yield (response variable) on NDVI values (predictor) collected at ZGS 16 across all environments (2015-2016).

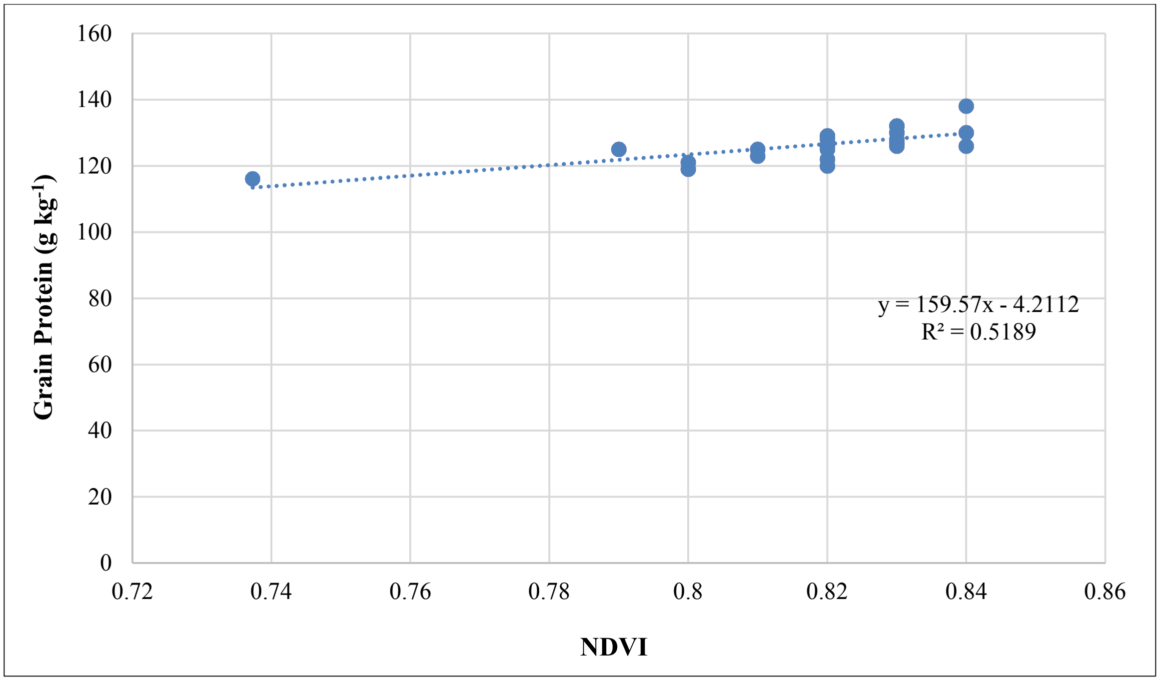

Figure 4. Linear regression of grain protein content (response variable) on NDVI values (predictor) collected at ZGS 31 across all environments (2015-2016).

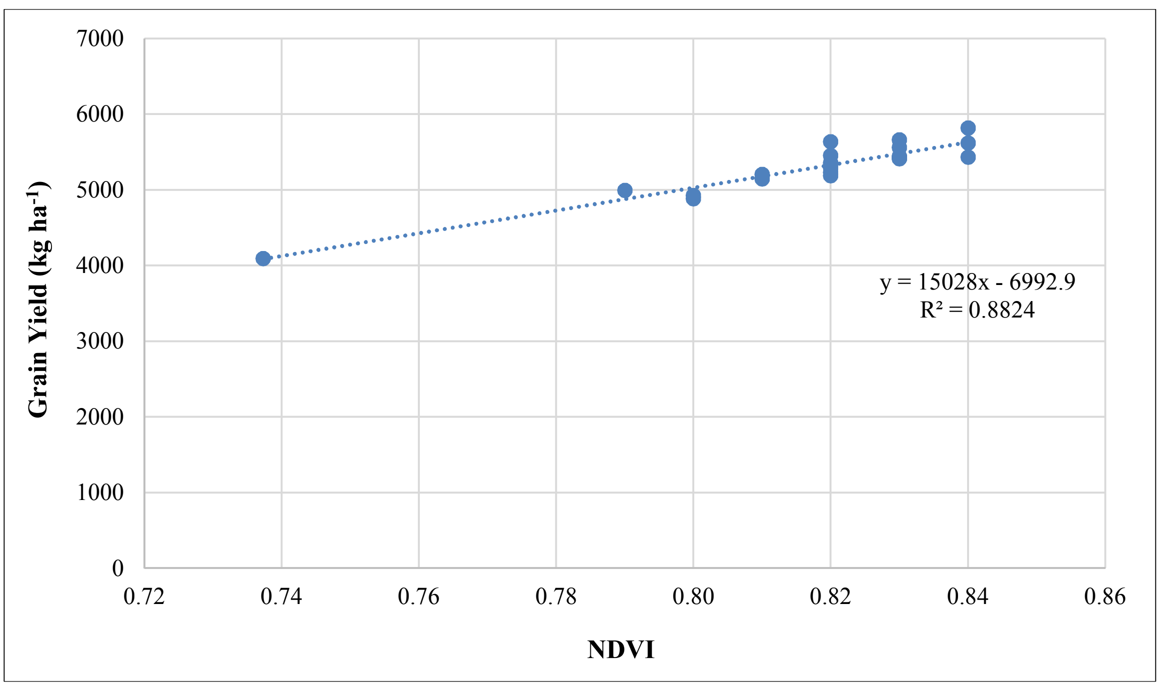

Figure 5. Linear regression of grain yield (response variable) on normalized NDVI values (predictor) collected at ZGS 31 across all environments (2015-2016).

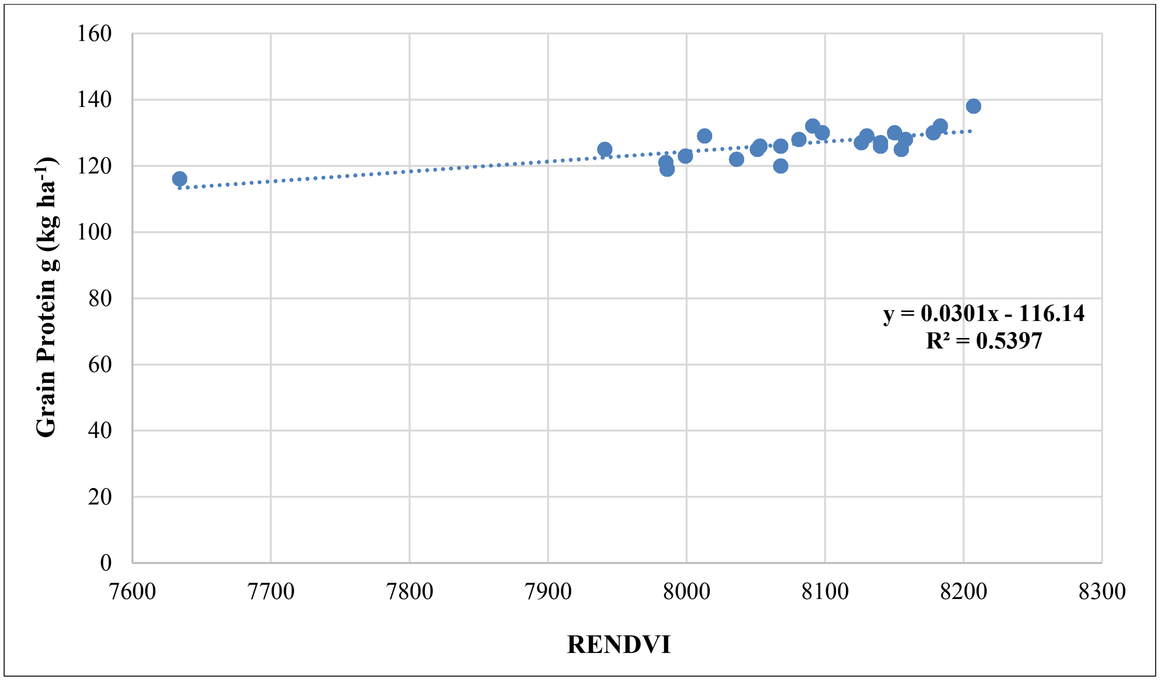

Figure 6. Linear regression of grain protein content (response variable) on RENDVI values (predictor) collected at ZGS 50 across all environments (2015-2016).

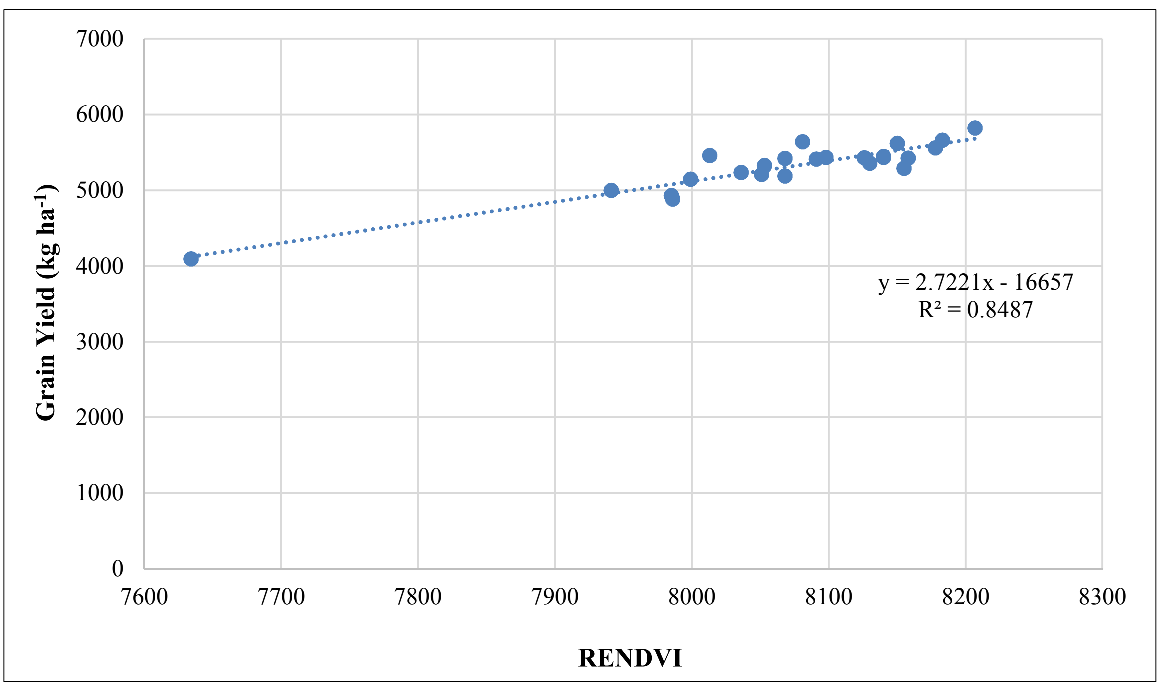

Figure 7. Linear regression of grain yield (response variable) on RENDVI values (predictor) collected at ZGS 50 across all environments (2015-2016).

CONCLUSION

Based on the environments sampled in 2015 and 2016, PCU shows promise in increasing protein content in HRSW over urea alone. This may be associated with more N availability to the plant when protein is developing in the grain. Overall, spring N applications improved grain protein and yield when compared to fall applications. Blends of PCU and urea at a 50:50 ratios in both spring and fall had a similar protein response as the 75:25 blend and the 100% PCU rate, therefore it would be more economical to use the lower rate PCU when blending with urea.

Polymer-coated urea shows promise as an N source that can be safely applied in the fall as an alternative to urea. However, the profitability of PCU for enhanced protein management will depend on the protein premium/discount when the grain is marketed, as protein increases were generally modest.

The potential for PCU to limit N loss increases in sandy or water-logged soils, or in environment conditions that are more likely to be susceptible to N loss. Although the highest rates of PCU improved grain yield and protein, it may be more economical to apply PCU blended with urea rather than 100 percent PCU, as the higher fertilizer costs will affect profitability when selling the grain. Further research in more environments will allow for additional data and insight into improving N-use efficiency in HRSW with the products tested, as N losses are driven by environmental factors.

Nitrapyrin and NBPT additives can be effective in limiting N losses to surface applied urea. However, environmental factors such as rainfall frequency and intensity can limit potential to decrease N loss through leaching, denitrification, and volatilization. The application of these additives would prove most economical when applied during conditions favorable for NH_3 volatilization. When determining the need for an alternative N product, growers must take into consideration the potential for N loss in a particular environment, as these products add additional cost to growers.

The NDVI values from the GreenSeeker had higher correlations between grain protein and yield at ZGS 31 rather than the earlier reading at ZGS 16. Overall, the highest correlation coefficients were between NDVI/RENDVI and grain yield, which were consistently higher than NDVI/RENDVI and grain protein correlations, regardless of the growth stage at the time of the readings. The best NDVI measurements for predicting grain yield and protein were taken at ZGS 31. If measurements collected at ZGS 31 indicate protein concentration will be low, growers would have adequate time to apply a late-season N application.

Values from RENDVI measurements taken at ZGS 50 were quite high for yield and had the highest correlation for grain protein compared to the NDVI values from ZGS 31. The RENDVI values obtained in this study show promise in predicting protein and/or yield, however, since the RapidSCAN sensor is a relatively recent technology, future experiments are needed to determine if RENDVI measurements collected at different growth stages can predict significant differences in grain protein and yield.

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