CROP SENSORS AS IN-SEASON NITROGEN MANAGEMENT TOOL FOR WINTER WHEAT IN WISCONSIN

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ABSTRACT

In Wisconsin, current winter wheat (*Triticum aestivum* L.) nitrogen (N) rate guidelines are determined by soil type, previous crop, and pre-plant soil nitrate test (PPNT). Nitrogen management may be improved through site-specific assessments of N need in the spring, offering a more effective use of top-dressed N. The study objective was to determine if crop reflectance measurements could be used to determine optimal in-season N rates on silt loam soils in eastern Wisconsin. This study evaluated the effect of ammonium nitrate applied at 0 to 167 kg N ha^{-1}, in 33 kg N ha^{-1} increments, top-dressed at green-up (GU) or Zadoks growth stage 30 (GS 30), on canopy reflectance, whole plant and grain N uptake, and yield.

Field experiments were conducted at two and three farms, in 2014 and 2015, respectively, where crop canopy reflectance measurements, using the Holland Scientific Crop Circle ACS-430 (Holland Scientific, Inc., Lincoln, NE), were collected from May (approximately GS 25) to mid-June (GS 40). Whole plant samples were collected at GS 30 in 2014. In 2015, whole plant samples were collected at GU, GS 30, and GS 40 and soil samples 0 to 30 cm were collected at GS 30. All plant samples were analyzed for total N and all soil samples were analyzed for NO_3-N and NH_4-N. In 2014, both normalized difference vegetation index (NDVI) and normalized difference red-edge index (NDRE) at GS 30 were significantly positively correlated with GS 30 N uptake. A quadratic-plateau regression model had the best fit for yield, NDVI, or NDRE response to N rate at both locations.

INTRODUCTION

Nitrogen is an essential mineral nutrient and is often one of the most limiting factors. While N losses can be extremely variable and weather dependent, applying too much N increases the risk of lodging (Bundy and Andraski, 2004), therefore increasing the potential for disease, contamination, harvest delay, and yield loss (Baethgen and Alley, 1989b; Scharf and Alley, 1993). Applying too little N results in plants having fewer tillers, reduced yields, and poor nitrogen use efficiency (NUE) (Ayoub, 1974; Knowles et al., 1994). As a result, preventing loss and applying at or near the timing of highest N uptake, in order to produce optimum conditions, are crucial for wheat production.

With proper N fertilization timing, yields can be improved. A successful N management approach for predicting optimum yield includes plant tissue analysis to determine N concentrations in wheat plants at specific growth stages (Baethgen and Alley, 1989b; Bundy and Andraski, 2004). Stone (1996) found that leaf N uptake could be used to assess the availability of N in the soil and predict fertilizer N requirement when samples were collected between GS 20 (tiller initiation) to GS 30 (stem elongation).

Despite the benefit of tissue sampling to determine optimum N applications, this practice can be extremely tedious and is not widely accepted by producers (Flowers et al., 2001). However, crop canopy reflectance sensors are tools that can be used to assess the N status of several crops including corn, soybean, and wheat. Creating and implementing N recommendations using this sensor technology can greatly reduce time spent assessing fields.

Crop canopy reflectance is determined using a sensor, which evaluates the amount of light reflected at specific wavelengths from pigments found in chlorophyll and carotenoids in a crop canopy to the sensor (Thomas and Gausman, 1977). The exact wavelength values are specific to the type of sensor being used. However, each general waveband is influenced by plant characteristics including plant morphology, leaf surface properties, internal structure, and the concentration and distribution of biochemical components (Phillips et al., 2004). For example, reduced leaf chlorophyll, can be measured using a sensor (Thomas and Gausman, 1977). Reflectance has been related to N status and yield, allowing for the prediction of N need, increasing N use efficiency and profitability, while protecting the environment (Schepers and Holland, 2011).

Wavelengths that are included in most sensors are the red (620-700 nm), near infrared (NIR, >740 nm), and red edge (700-740 nm). Each of these wavebands gives an estimation of different components found in plants. The red waveband estimates chlorophyll content. While leaf pigments and cell-wall cellulose are transparent in the NIR waveband, this makes this waveband highly responsive to plant biomass (Flowers et al., 2001). Determining canopy N content early on in the growing season, especially in winter wheat, can be difficult due to different canopy structure, limited cover, and soil reflection (Cammarano et al., 2011). Darker soils result in lower NIR reflectance values compared to lighter soils (Huete, 1987; Phillips et al., 2004); it is not until the soft dough stage that wheat reflectance becomes nearly independent of soil reflectance (Chance, 1977). The red edge estimates chlorophyll status and leaf characteristics (Phillips et al., 2004).

Vegetative indices can be calculated using reflectance in these wavebands. The NDVI (Rouse et al., 1974), is calculated as follows

$$NDVI = \frac{(R_{NIR} - R_{RED})}{(R_{NIR} + R_{RED})}$$

and is sensitive to living biomass. The NDRE (Barnes et al., 2000) is calculated by

$$NDRE = \frac{R_{NIR} - R_{EDGE}}{R_{NIR} + R_{EDGE}}$$

These normalized difference ratios can then be used to calculate the canopy chlorophyll content index (CCCI), which is sensitive to chlorophyll content (Barnes et al., 2000) and is calculated by dividing NDRE by NDVI.

Other suggested ways of modifying reflectance data include Holland and Schepers' (2010) sufficiency index (SI), where sensor data is normalizing based on of the sensor value from a high N reference strip. Another concept provided by Raun et al. (2001) is the in-season estimate of yield (INSEY) where the sum of the NDVI collected from two different dates is divided by the change in growing degree days (GDD) between the two dates.

The objective of this study was to determine if the measurement of active light reflectance using crop-canopy sensors at various growth stages can be related to yield and optimum N rate for wheat grown in Wisconsin. Determining if there is a relationship between the sensor data and yield parameters will aid in the development of an N recommendation algorithm for winter wheat in Wisconsin.

MATERIAL AND METHODS

Site Conditions and Crop Production Practices

Research was conducted in eastern Wisconsin at two and three locations on private farms during the 2014 and 2015 crop years, respectively. Sites were located in Chilton (Calumet County), Lamartine (Fond du Lac County), and Pipe (Fond du Lac County).

The cultivar Pioneer P25R40 was planted at 3.7 million viable seeds per hectare. Chilton was planted on 27 Sept. 2014 and 29 Sept. 2015. Lamartine sites were planted on 2 Oct. for both years. Pipe was planted 2 Oct. and 29 Sept. in 2014 and 2015, respectively. Winter wheat was grown following University of Wisconsin recommended crop management practices. Plots were 2.4 m wide by 7.6 m long with 0.19 m row spacing, and later trimmed to 6.4 m long. The center 7 rows were harvested, resulting in a total harvest area of 1.5 m wide by 6.4 m long (9.7 m^2).

Treatments

The experimental design at all locations was a randomized complete block with four replications. In 2014, the treatments included a control, ammonium nitrate applied at 33, 67, 100, and 133 kg N ha^{-1} at GU, ammonium nitrate applied at 33, 67, 100, and 133 kg N ha^{-1} at GS 30, and a single fall application of 133 kg N ha^{-1} as SuperU® 133 kg N ha^{-1} to represent a non-limiting N reference treatment for early season crop canopy reflectance measurements. In 2015, additional treatments of 167 kg N ha^{-1} as ammonium nitrate applied at GU or GS 30 were included.

Soil and plant measurements and canopy sensing

Soil samples were collected from 0 to 0.3 m at GS 30 from the control (no N) and all treatments where N was applied at GU and were analyzed for NO_3-N and NH_4-N using the single reagent vanadium chloride method of Doane and Horwáth (2003) and the Berthelot method (Nelson, 1983; Kempers and Zweers, 1986).

Two 1-m sections of aboveground whole-plant biomass were collected at GS 30 in 2014 and GU, GS 30, and GS 40 in 2015. Treatments sampled at GU include: the control (0 N) and 133 kg N ha^{-1} SuperU® broadcast in the fall. GS 30 samples were collected from the control (no N) and all treatments where N was applied at GU. GS 40 samples were collected from the control (no N) and where 67 and 133 kg N ha^{-1} as ammonium nitrate was broadcast at GU. At physiological maturity, grain yields were determined by harvesting each plot with a self-propelled plot combine equipped with a grain gauge and moisture sensor.

All tissue and grain samples were immediately dried in a force-draft dryer at 66^{o}C. Samples were then ground to pass through a 1-mm sieve, and retained in plastic sample bags for total N analysis. Total N concentration was determined on all tissue and grain samples using a Kjeldahl digestion (Nelson and Sommers, 1973). The resulting solution was stored at 4^{o}C until further analysis, then diluted and analyzed using a modification of the ammonium determination method described above, to account for the low pH of the digested samples. Straw and grain N concentration were used to determine straw and grain N uptake. Finally, total plant N uptake (straw + grain) and apparent fertilizer-N use efficiencies were determined.

Crop spectral reflectance measurements were collected with a Holland Scientific Crop Circle ACS-430 hand held canopy reflectance sensor (Holland Scientific, Inc., Lincoln, NE), equipped with a 30^{o} field of view, providing output for the following characteristics: red (670 nm), red-edge (730 nm), and near infrared (NIR, >760 nm) wavelengths, NDRE and NDVI values. Data collection started 14 and 20 days after GU applied N in 2014 and 2015, respectfully, and ended at the dough stage (about 2 weeks before harvest) in 2014 and ended at GS 40 in 2015. Measurements were collected weekly at each site, by walking in the boarder row for each plot at approximately 1 m s^{-1} (Holland and Schepers, 2010), while holding the sensor approximately 30 inches above the fourth and fifth row of each plot.

Table 1. Date of fertilizer and crop canopy reflectance sensing for the 2014 and 2015.

Timing	Field task	2014	2015
GU	Fertilizer application (GS 21)	25 April	17 April
	Sensing (GS 23)	9 May	7 May
GS 30	Fertilizer application and sensing	21 May	15 May
GS 40	Sensing	29 May	27 May

Statistical Analysis

Grain yield response to N fertilizer was analyzed using PROC REG, for linear and quadratic models, and PROC NLIN, for linear-plateau and quadratic-plateau models, to find the best fit yield response model. The quadratic-plateau model fit the data best for all site years, except at Chilton in 2015 where a linear-plateau model was the best fit. The economic optimum N rate (EONR) was then calculated by setting the first derivative of the quadratic plateau model equal to the N:wheat price ratio of 0.05 ($0.32 kg^{-1} N:$260 Mg^{-1} wheat) and solving for the nitrogen rate.

NDVI, NDRE, and CCCI were calculated for each plot for each time of sensing. Correlation analysis was used to determine if any of these reflectance data collected at GU, GS 30, and GS 40 were related to soil NO_3-N collected at GS 30, N uptake at GS 30, yield, relative yield, or optimum N rate. Reflectance data used in correlation analysis included: the 730, 780, and 670 wavelengths; NDRE, NDVI, and CCCI vegetative indices; SI_{NDRE} and SI_{NDVI}; and the INSEY.

RESULTS AND DISCUSSION

In 2014, the effect of N application timing, applied at 133 kg N ha^{-1}, on grain yield was significant at both locations. The best time to apply N was at GU where the average yield for 2014 was 7.1 Mg ha^{-1} compared to 6.4 and 6.3 Mg ha^{-1} when N was applied at planting and GS 30, respectively. The EONR for GU applied N was 70 and 97 kg N ha^{-1} at Chilton and Lamartine, respectively. Whereas, EONR for GS 30 application timing was 65 and 107 kg N ha^{-1} at Chilton and Lamartine, respectively. The difference in EONR between application timings was relatively small, though a significant yield loss occurs with the later application at GS 30.

Similar interpretations can be observed from the 2015 growing season, where the effect of N application timing on yield proved that the fall and GU application timings were not significantly different from each other at Chilton and Pipe. However, GU always resulted in the best grain yield at all three locations. For GU applied N, the EONR was 67, 88 and 33 kg N ha^{-1} at Chilton, Lamartine, and Pipe, respectfully. Economic optimum N rate for the GS 30 application timing were 0, 118, and 0 kg N ha^{-1} at Chilton, Lamartine, and Pipe, respectfully. In 2015, high profile preplant nitrate levels, ranging from 121 to 148 kg N ha^{-1} could be the result of the lack of response to N at Chilton where N was applied at GS 30 and at Pipe where N was applied at either GU and GS 30. Since the GU N application timing is used for the Crop Circle comparisons, Pipe was eliminated from analysis.

For the remaining site years (Chilton and Lamartine in 2014 and 2015), there was a significant correlation between the 730, 780, and 670 wavelengths and grain yield, relative yield, and GS 30 N uptake. After modifying the wavelengths into the vegetative indices, NDRE and NDVI at GS 30 and GS 40 resulted in even stronger significant positive correlations (Table 2). Stronger positive correlations were observed as the growing season progressed (Figure 1).

Table 2. Correlation coefficients for Chilton and Lamartine in 2014 and 2015, between three different crop canopy reflectance data collection times (GU, GS 30, and GS 40) and select yield components.

	GS 30 Soil NO_3-N	GS 30 N uptake	GS 40 N uptake	Grain Yield	Relative Yield
GS 30 Soil	**1.00**				
GS 30 N uptake	0.184	**1.00**			
GS 40 N uptake	0.453*	0.141	**1.00**		
Grain yield	0.065	0.580***	-0.060	**1.00**	
Relative yield	0.300*	0.538***	0.267	0.906***	**1.00**
GU NDRE	0.017	0.439***	0.093	0.279***	0.446***
GU NDVI	0.002	0.440***	0.113	0.283***	0.448***
GU CCCI	0.094	-0.054	-0.182	0.120	-0.104
GU SI-NDRE	-0.126	0.540***	-0.077	0.443***	0.489***
GU SI-NDVI	-0.111	0.522***	-0.018	0.413***	0.484***
GS 30 NDRE	-0.105	0.546***	-0.181	0.563***	0.518***
GS 30 NDVI	-0.207	0.540***	-0.317	0.623***	0.498***
GS 30 CCCI	0.479***	0.073	0.383	-0.192	0.155
GS 30 SI-NDRE	0.048	0.453***	0.080	0.398**	0.491***
GS 30 SI-NDVI	0.039	0.409***	0.112	0.372*	0.477***
GS 40 NDRE	0.315**	0.580***	0.071	0.618***	0.626***
GS 40 NDVI	0.337**	0.457***	0.093	0.476***	0.538***
GS 40 CCCI	0.192	0.607***	0.035	0.675***	0.597***
GS 40 SI-NDRE	0.397**	0.540***	0.191	0.538***	0.619***
GS 40 SI-NDVI	0.345**	0.452***	0.107	0.467***	0.537***
INSEY-NDRE	-0.130	0.568***	-0.157	0.541***	0.523***
INSEY-NDVI	-0.204	0.576**	-0.231	0.592***	0.521***

*, **, *** Significant at 0.10, 0.05, <0.01 probability level, respectively.

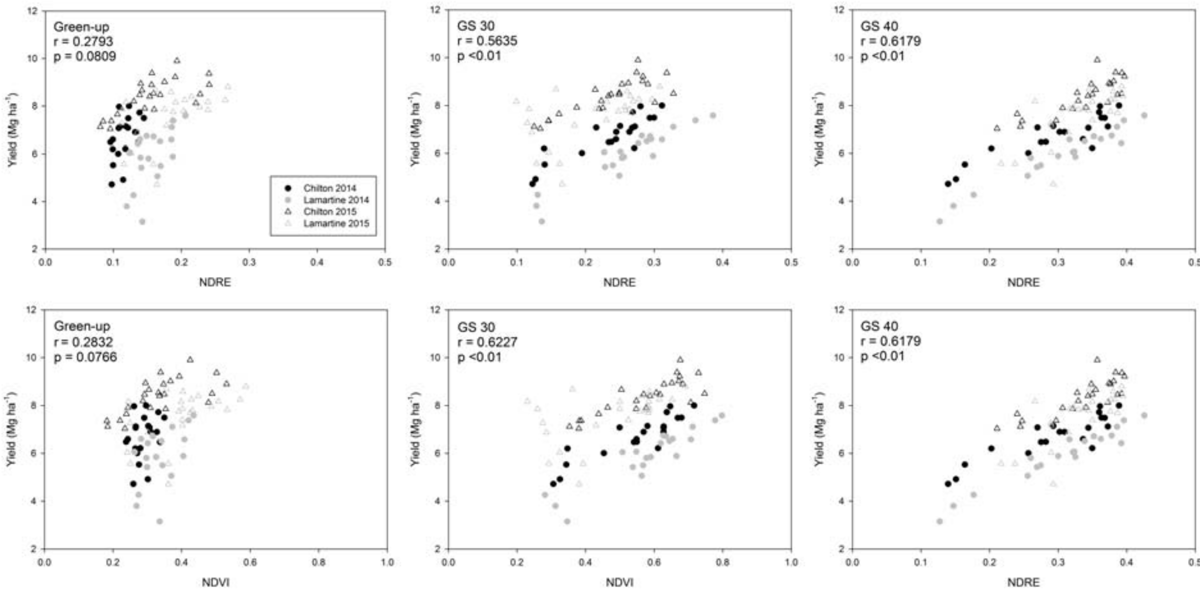

Figure 1. Wheat grain yield response to NDRE and NDVI vegetation indices at three different times (Green-up, GS 30, and GS 40).

Unlike Holland and Schepers (2010) observed quadratic-plateau relationship between SI and N rate, none of the Wisconsin SI calculations compared to N rate produced any sort of similar correlation until GS 40 (data not shown). Based on our data and common practice, N application is not recommended at GS 40 because the wheat is at the boot stage, where the head has moved above ground level, and any wheel traffic could result in damage to the head/inflorescence causing yield loss. On the other hand, the INSEY relationship developed by Raun et al. (2001) calculated with NDRE and NDVI between the GU and GS 30 sensing dates, did produce a positive significant correlation with GS 30 N uptake, yield (Figure 2), and relative yield with data collected in Wisconsin.

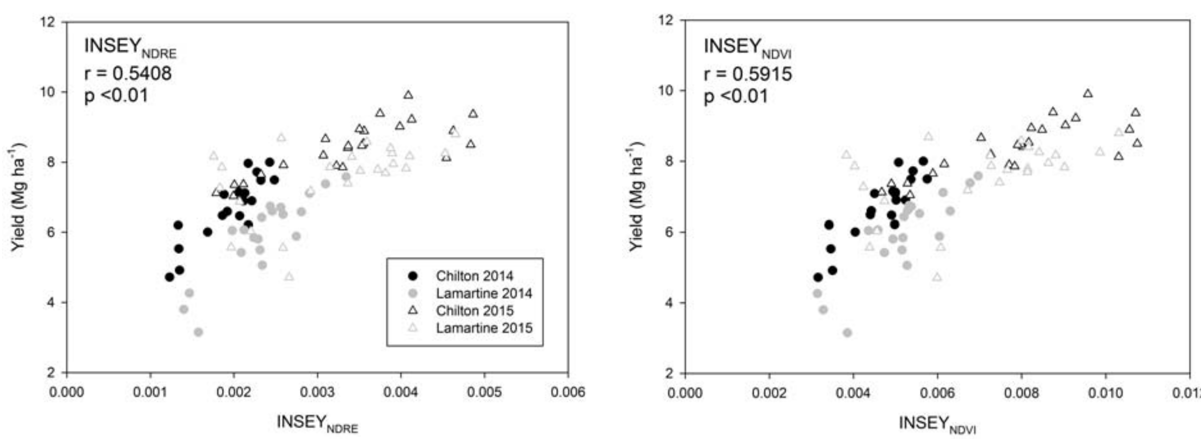

Figure 2. Wheat grain yield response to $INSEY_{NDRE}$ and $INSEY_{NDVI}$ at Chilton and Lamartine in 2014 and 2015.

SUMMARY

The optimum N application timing was at green-up in 2014, where grain yields were significantly greater than the fall and GS 30 timings. In 2015, fall and green-up grain yields were not significantly different, although yields where N was applied at green-up had the highest grain yield.

The objective was to determine if crop reflectance measurements could be used to determine optimal in-season N rates on silt loam soils in eastern Wisconsin. We observed that there are relationships that can be observed between crop canopy reflectance data and select yield parameters. Stronger correlations occur with later sensing; however, if N is applied at GS 30 or later in the growing season yields are significantly reduced compared to application at GU.

There were significant positive correlations between INSEY, calculated with NDVI and NDRE, and yield or GS 30 N uptake. However, using INSEY is not practical because crop canopy reflectance data needs to be collected at two different timings and an N recommendation is made after the second date of sensing. In this case, we calculated INSEY using data from GU and about a week later at GS 30. But, if a producer is able to get into the field at GU, N should be applied at this time. Applying N at GU will not only reduce the cost and damage of additional traffic in the field, but will prevent the inevitable yield loss observed with later N application times for all site years in this study.

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