RELATIONSHIP BETWEEN RESPONSE INDICES MEASURED IN-SEASON AND AT HARVEST IN WINTER WHEAT

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ABSTRACT

Current methods for making nitrogen recommendations in winter wheat (*Triticum aestivum* L.) do not adjust for in-season temporal variability of plant available non-fertilizer nitrogen (N) sources. The purpose of this study was to compare the use of different nitrogen response indices determined in-season (RI_{NDVI} and $RI_{PLANTHEIGHT}$) to the nitrogen response index measured at harvest ($RI_{HARVEST}$). In addition, this study evaluated the use of the in-season response indices for determining topdress nitrogen rates for winter wheat. Nine experiments were conducted over two years at eight different locations. A randomized complete block design with nine different treatments and four replications was used at each location. Preplant nitrogen source was ammonia nitrate (34-0-0). At Feekes 4-6, RI_{NDVI} was measured to determine the topdress nitrogen rates. Both RI_{NDVI} and $RI_{PLANTHEIGHT}$ were able to predict $RI_{HARVEST}$ ($r^2 = 0.75$ and $r^2 = 0.74$, respectively). Because the sensor based approach for making N recommendations relies on information obtained from in-season sensor readings, RI_{NDVI} should be used to estimate a site's potential for response to additional nitrogen. Use of the response index will allow producers to move away from reliance on preplant application of N and start managing N based on the likelihood of achieving an economical response to N fertilizer.

INTRODUCTION

Common N fertility management practices implemented by producers usually involve a soil-based approach where fields are soil sampled to evaluate for nitrate nitrogen in the soil. This is then subtracted from the amount of N needed to reach a certain yield goal and the balance applied as fertilizer N, typically prior to seeding. This research aims to look at an alternative approach utilizing crop-based evaluations of N status and in-season N application based on crop needs.

Johnson and Raun (2003) proposed a response index, which measures the plant response to nitrogen fertilizer in terms of grain yield in a particular growing season. A response index was calculated by taking the highest yielding fertilized grain plot and dividing by the control yield (0 N applied). They further developed a method to assist winter wheat producers in determining in-season response to additional N fertilizer. This method involved installing a strip of N fertilizer that is twice the rate (or non-N-limiting) used during pre-plant fertilization. Implementing this zone allows the producer to visually quantify the likelihood of achieving an in-season response to N fertilizer. If the non-N-limiting strip is not visible to the producer, it would indicate that minimal or no N response is likely since adequate N was already available from preplant fertilization, N mineralization, and/or rainfall.

The ability to predict the magnitude of which winter wheat will respond to additional topdress N fertilizer during the growing season would provide one way of increasing Nitrogen use efficiency (NUE). Furthermore, given the low prices for hard red winter wheat and associated high prices of N fertilizer, wheat producers are looking for methods to cut fertilizer costs and maintain yield levels. A one percent increase in NUE would save approximately $234.658,462 worldwide while a 20 percent increase would have savings in excess of $4.7 billion per year (Raun and Johnson 1999).

In 1999, the United States used more than 11,165,310 Mg of nitrogen (FAO 2001). It is believed that a large portion of environmental pollution from N sources comes from their use in agriculture cropping systems. The pollution results when producers apply excess N to insure against a change in growing conditions where the crop might benefit from the extra N that might otherwise result in reduced yield. Goolsby et. al. (2001) reported that the mean annual discharged flux of all forms of N in the Mississippi and Atchafalaya River Basin was 1,568,000 Mt yr^{-1} for the time period between 1980 to 1996. Jaynes et. al. (2001) reported in a study of N in tile drainage that even at the lowest N treatment rate (67 kg N ha^{-1}), NO_3-N levels exceeded the maximum contaminant limit of 10 mg NO_3-N L^{-1} set by the USEPA for drinking water. With these pollution problems, methods for applying N to a cropping system that will increase efficiency and maintain or increase yield while lowering the amount of nitrogen contamination in fresh water supplies must be developed by researchers and employed by agriculture producers.

With the further development of optical sensing technology, many researchers have been investigating the possibility of predicting crop yield by light absorbance (Coldwell, 1954; Jordan, 1969; Tucker, 1979; Sellers, 1985,1987; Stone et. al., 1996 a,b). Ma et. al. (1996) reported that canopy light reflectance values at 600 nm (Red light) and 800 nm (NIR light), could be used to calculate the Normalized Difference Vegetative Index (NDVI). NDVI is defined as ((NIR - RED) / (NIR + RED)) and was found to be strongly correlated with grain yield. This correlation increased up to anthesis. They also stated that NDVI was better at differentiating N treatment effects than any other wave bands and that NDVI was also correlated with leaf area and leaf chlorophyll.

Mullen et. al. (2003) reported that computing an in-season response index (RI) from N induced NDVI differences (RI_{NDVI}) at Feekes 5 (Large, 1954) over 4 years taken from 22 locations was well-correlated (r^2 = 0.56) with RI measured at harvest ($RI_{HARVEST}$). The RI_{NDVI} was determined by dividing plots that were non-N-limiting by a zero N check plot. A method for finding a reliable, in-season estimate of the crop's response to additional topdress N that does not rely on an induced N non-limiting area would be desirable. This method could reliably predict the final response without incurring additional costs of installing a non-N-limiting strip or area, thus improving overall profitability. Work done on the field element size, and the micro-variability of mobile and immobile soil nutrients, illustrates the highly variable nature of soil nutrients (Solie et. al. 1999; Raun et. al. 1998). Knowing the optical sensor field element size (Solie et.al. 1996) for measuring plant N uptake using light reflectance is <1.5 m^2, it may be possible to develop a reliable in-season estimate of RI based on spatial variability (RI_{SV}) of plant available soil N. RI_{SV} is defined by the equation: (Mean NDVI + 1 standard error) / (Mean NDVI – 1 standard error). The mean and the standard error for NDVI is calculated from all randomly selected field element sizes measured. RI_{SV} can be determined from sensor readings collected anywhere within fields not having the non-N-limiting (N-rich) strip.

Furthermore, a method for producers to reliably measure a site's potential response to additional N, without using a sensor to measure RI_{NDVI}, needs further evaluation. This non-sensor based in-season RI would be of benefit to farmers in developing countries or a farmer in a developed country who cannot afford a sensor or who is skeptical of its use in an N management scheme. A potential non-sensor based in-season response index could be based on differences in any crop characteristic that responds to N. Crop canopy height ($RI_{PLANTHEIGHT}$) is responsive to N availability and should be a good measure, right before making a topdress N application, which is the same time one would measure RI_{NDVI} with a sensor. $RI_{PLANTHEIGHT}$ would be measured the same way as RI_{NDVI}, (Mean plant height of N-rich) / (Mean plant height of check). The objectives of this experiment were to: 1) determine the relationship between in-season spectral reflectance measured response index (RI) and the RI measured at harvest; 2) determine the relationship between crop canopy height at the time of application of top-dress N fertilization and RI based on spectral reflectance.

MATERIALS AND METHODS

A randomized complete block design was used with nine different N management treatments replicated four times at each site. All preplant treatments used ammonium nitrate (34-0-0) as the fertilizer N source. Preplant treatments were incorporated by hand after application. All sites were planted in a 19cm row spacing using a Tye® small grain drill except for the Tipton 2003 site, which was planted in 25cm row spacing. A light tillage operation, using a field cultivator, was used on an as needed basis prior to planting for weed control. All plots were harvested by hand, removing the center 1m^2 from of each plot. All plots were cut at ground level, and dry weights taken before grain was threshed. All statistical analysis was completed using SAS (2000).

NDVI was measured between Feekes growth stages 4 to 6 (Large 1954) on all plots both years. The different N treatments in this study had varied amounts of preplant and/or topdress N applications. The focus of this paper is on treatment one (check, 0N) and treatment eight (90 kg N ha^{-1}) for estimating the in-season response index based on differences of a non-N-limiting area and a check (0 N). Furthermore, treatments one to five (topdress N only) were used for estimating RI_{SV} before topdress N was applied.

An RI based on NDVI (RI_{NDVI}) was determined by taking sensor readings in the induced non-N-limiting plots (preplant application of 90 kg N ha^{-1}) and dividing by the check treatment (0 N). RI_{SV} was calculated from NDVI readings of treatments one to five using the same NDVI readings taken for calculating topdress rates using the NFOA algorithms. These treatments had zero additions of N fertilizer either preplant or topdress when the sensor readings were taken. This allowed for simulation of NDVI readings taken from 20 randomly selected 1.5 m^2 field element sizes in the same field. The NDVI of 20 plots means were used to calculate an overall average and a standard error. Thus, RI_{SV} = (Overall mean NDVI + 1 Standard error) / (Overall mean NDVI - 1 Standard error).

$RI_{PLANTHEIGHT}$ was determined using the same treatments as RI_{NDVI}. Plant height was measured with a meter stick by recording the length from the base immediately above the soil and extending leaves along the meter stick to the nearest millimeter. Five measurements were taken from each plot and a mean was figured for each of the two treatments used to determine the response index. $RI_{HARVEST}$ was determined by dividing the grain yield of treatment eight by the grain yield of treatment one.

NDVI was measured using a GreenSeeker ™ hand held optical sensor unit. The handheld optical sensor unit measures NDVI using self-contained illumination in both the red (650 $\pm$ 10 nm full width half magnitude (FWHM)) and NIR (770 $\pm$ 10 nm FWHM) light bands. The device measures the fraction of the emitted light in the sensed areas that is returned to the sensor (reflectance). These reflectances are used to compute NDVI according to the following formula: $NDVI = (F_{NIR} - F_{RED}) / (F_{NIR} + F_{RED})$, where F_{NIR} is the fraction of emitted NIR radiation returned from the sensed area, and F_{RED} is the fraction of emitted red radiation returned from the sensed area. The area sensed by this handheld unit is 0.6 by 0.01m. The sensor was passed over the entire plot area and an average NDVI was determined from all readings taken (approximately 15 readings per plot). The sensor outputs an NDVI value at a rate of 10 readings per second. The sensor was held at height of approximately 0.9 m above the crop canopy.

RESULTS AND DISCUSSION

Based on two years and nine experimental sites over eight different locations, the degree of response to N varied by year and location (Figure 1). This implies a need for N recommendations to have the flexibility to encompass temporal variations at different locations. RI_{NDVI} was a good indicator of a site's potential responsiveness to additional N. Across nine sites different environments and two years, RI_{NDVI} was positively and significantly correlated with $RI_{HARVEST}$ (Figure 1). The slope of this line is greater than that reported by Mullen et. al. (2003) which was close to one (1.06).

However, looking at that set of data, six of the points for both RI_{NDVI} and $RI_{HARVEST}$ are below 1.25 and 1.26 respectively. This was encouraging since RI_{NDVI} indicated that a site might be marginally responsive to additional N, and was confirmed with a low $RI_{HARVEST}$. A site was considered non-responsive if the RI_{NDVI} was from 1.0 to 1.10 and marginally responsive from >1.10 <1.25. At the marginally responsive range, the increase in grain yield from additional N may not have an economical return on the expenditure for the N fertilizer. In the non-responsive range, it is very unlikely that the producer would observe an economic return on the N fertilizer dollar spent to obtain the small increase in grain yield.

It was interesting to note that the slope of RI_{NDVI} versus $RI_{HARVEST}$ is not close to 1.0. Lukina et. al (2001) found that at Feekes 4-6, winter wheat can take up more than 45 kg N ha^{-1}. This amount represented over half of the total N that would be in the grain at harvest. So, at early growth stages, winter wheat has taken up a large portion of the N that the plant needs to meet its yield potential. Thus, one would expect that the relationship between the response indices would be very similar to and would have a slope of one.

$RI_{PLANTHEIGHT}$ over all nine locations was strongly correlated with $RI_{HARVEST}$ ($r^2 = 0.74$) (Figure 2). This is very encouraging since it allows for producers to make a reliable estimate of $RI_{HARVEST}$ without the use of a handheld sensor. This could be very useful to producers in developing countries that farm only a few hectares and cannot afford a hand held sensor, but can still capitalize on the use of managing N for temporal variability by using a N-rich strip. $RI_{PLANTHEIGHT}$ was also correlated with RI_{NDVI} over nine sites and two years ($r^2 = 0.61$)(Figure not reported).

RI_{SV} was poorly correlated with both with $RI_{HARVEST}$ and RI_{NDVI} (Figures 3). The failure of RI_{SV} to predict $RI_{HARVEST}$ or estimate RI_{NDVI} could be due to not having enough samples of $<1.5m^2$ measured in this study. Further investigation is needed to determine how many field elements $<$ 1.5 m^2 would be needed to reliably predict and estimate both $RI_{HARVEST}$ and RI_{NDVI} in a given field. In addition, RI_{SV} assumes that the variability measured by the sensor is due to spatial difference in N. RI_{SV} should be measured only when a crop stand visually appears uniform and is not affected by any other factors that could affect the variation in NDVI measured in random field elements. Factors that could contribute to the failure of RI_{SV} to predict $RI_{HARVEST}$ could include uneven plant stands, variations in tiller density, differences in plant available water in the soil solution, drainage, and degree and direction of facing slope. Any soil parameter that affects the growth of the crop other than N status of the soil from one field element to another would make RI_{SV} an unreliable estimate of the crops potential responsiveness to additional N.

In-season N management schemes that incorporate an in-season response index (RI_{NDVI} or $RI_{PLANTHEIGHT}$) will allow for producers to quantify the likelihood of achieving an economical response to additional N, tailored to that site, for that growing season. If producers are to realize full potential of this system, preplant N rates must be reduced. By reducing preplant N rates, they can start to take advantage of years where little or no N is needed to achieve maximum yields. This helps support the effectiveness of using a sensor based approach for making N recommendations over the current industry standard of yield goals and preplant soil samples for residual nitrate. Even if producers do not treat within field spatial variability, the use of an N-rich strip and a check plot will allow them to adjust for temporal variability, and large-scale variability (by field). This will help to improve their NUE over current N management practices.

CONCLUSION

RI_{NDVI} was related to $RI_{HARVEST}$ over 9 locations and two years. Use of the response index will allow producers to move away from reliance on preplant application of N and to start managing N based on the likelihood of achieving an economical response to N fertilizer. This can only be done when a N-rich strip is installed and the N management practice allows for N rates to be adjusted by season and location.

$RI_{PLANTHEIGHT}$ could be a very useful tool for small farmers in developing countries who cannot or do not want to initially undergo the cost of a handheld sensor. Furthermore, $RI_{PLANTHEIGHT}$ should continue to be evaluated as a potential aid when using RI_{NDVI}. An example could be at a site where RI_{NDVI} has indicated that it would be marginal in its response to additional N, and that could be confirmed with $RI_{PLANTHEIGHT}$. The fact that $RI_{PLANTHEIGHT}$ was strongly correlated with $RI_{HARVEST}$ indicates that it can be used instead of RI_{NDVI}. Yet, the N recommendations used in this study rely solely on information derived from the sensors to generate NDVI. Thus, RI_{NDVI} is still a reliable tool that should be used because the measurements are easy and rapid. For a producer that has many fields to evaluate in a short time, taking 40 to 50 plant measurements per site, with a meter stick, and then calculating averages from the data collected could take up valuable time and labor. RI_{SV} should not be used to determine RI_{NDVI} or $RI_{HARVEST}$. Of the three response indices for predicting a site's potential responsiveness to N, this was the poorest. Part of the problem in this study was possible lack of data collected to obtain enough samples of the total population with the field. Also, this response index assumes that the variability measured by the sensor is due to N status of the soil alone. That can be a risky assumption when all the possible factors that could be affecting the measured variability are examined.

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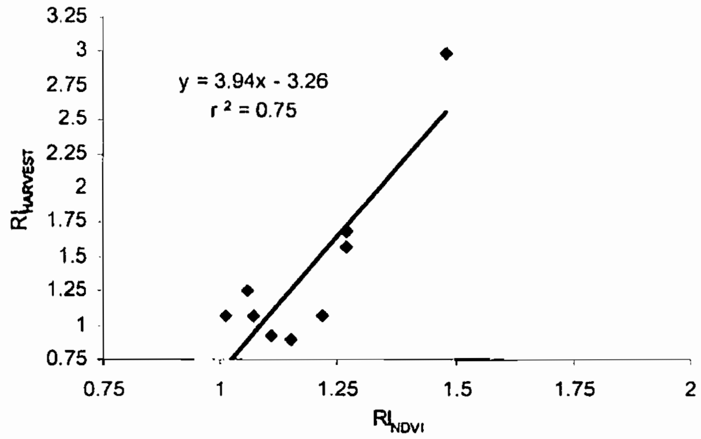

Figure 1: RI_{NDVI} at Feekes 4-6 versus $RI_{HARVEST}$ at nine sites for 2001-2003 crop years

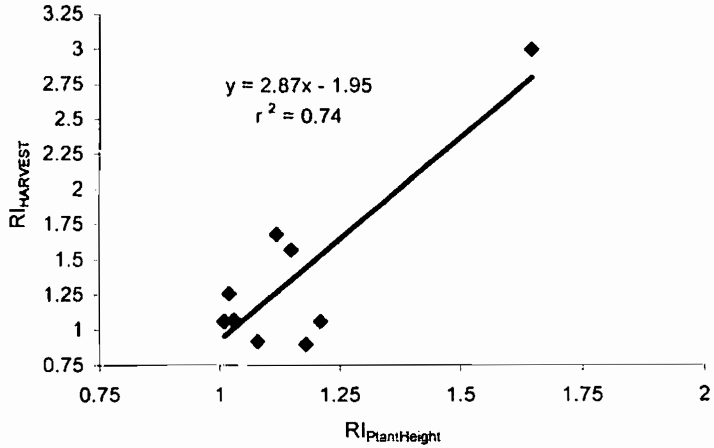

Figure 2: $RI_{Plantheight}$ at Feekes 4-6 versus $RI_{HARVEST}$ at nine sites for 2001-2003 crop years

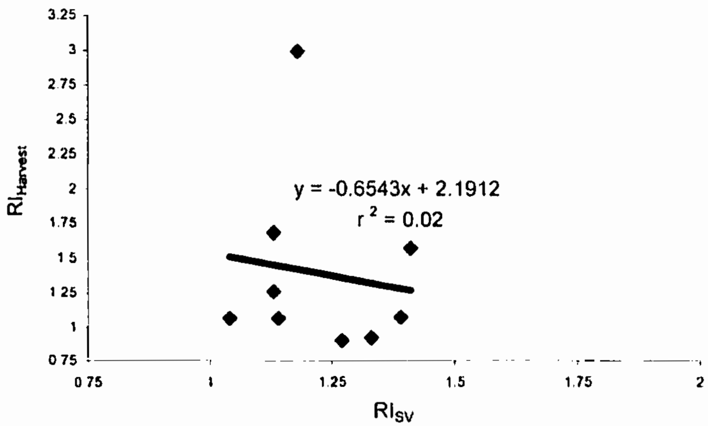

Figure 3: RI_{SV} at Feekes 4-6 versus $RI_{HARVEST}$ at nine sites for 2001-2003 crop years

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