REAL-TIME, IN-SEASON NITROGEN APPLICATION USING OPTICAL SENSORS

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ABSTRACT

Variable rate application of fertilizer materials for cereal crop production has been an intense area of research for the last several years. Non-destructive methods of plant analysis, namely crop reflectance based vegetative indices, have been evaluated and researched to determine which provides the best in-season information to make fertilizer recommendations. Because nitrogen (N) fertilizer is typically the largest seasonal crop input (with the exception of water, if irrigation is available), much of the research has focused on ways to use optical sensors to make better N in-season management decisions. Researchers at Oklahoma State University have conducted work on winter wheat since 1992 to develop such a system to treat temporal and spatially variability using red and near-infrared bands. In fact, their research has resulted in a commercially available variable rate applicator for N application in winter/spring wheat. The current algorithm, "WheatN1.0", can be separated into two distinct components: 1) mid-season prediction of grain yield, determined by dividing the normalized difference vegetative index (NDVI) by the number of days from planting to sensing where growing degree days (GDD) are greater than zero (estimate of biomass produced per day on the specific date when sensor readings are collected), and 2) estimating temporally dependent responsiveness to applied N by placing non-N-limiting strips in production fields each year, and comparing these to the farmer practice (response index). These two components are then combined to produce a functional algorithm that determines an N application rate for each 0.4 m2 based on estimated plant removal and adjusted by field responsiveness to applied N. Basing in-season N fertilizer recommendations on estimated crop removal and environmental responsiveness can increase nitrogen use efficiency (NUE) by 15% in winter wheat when compared to conventional methods. Using an active, optical sensor based algorithm to determine N rates can increase yields and decrease environmental contamination due excessive N fertilization.

INTRODUCTION

Current nitrogen use efficiency (NUE) of worldwide cereal crop production is estimated to be near 33% (Raun and Johnson, 1999), elucidating the need for more efficient methods of managing N. Nitrogen management strategies that address both temporal and spatial variability have the greatest chance of having an impact. Current N recommendations are typically determined using historical yield averages to set an "attainable" yield goal, which is multiplied by an assumed N requirement for each unit of yield expected (33 kg N/ha for every 1 Mg of winter wheat grain (Johnson et al., 2000) or 20 kg N/ha for every 1 Mg of corn grain (Schmitt et al., 1998)). Nitrogen is then typically applied preplant to satisfy estimated crop needs based on yield goal for the remainder of the growing season. Some producers may increase application rates above the recommended rate if they perceive there is an opportunity for a good year (Rehm and Schmitt, 1989; Johnson, 1991). Rehm and Schmitt (1989) also state that if moisture is limiting, yield goals based on previous yield averages is not advisable. This places the risk of predicting the crop season (good or bad production year) on the producer. This provides an opportunity for the use of optical sensors to make real-time, in-season N recommendations. The work presented here is a condensed version a recently submitted manuscript (Raun et al., 2004).

DISCUSSION

Estimate of Yield Potential

Early work by Stone et al. (1996) showed that early-season NDVI readings of winter wheat were highly correlated with plant biomass. Lukina et al. (2001) observed that NDVI readings taken at or near Feekes 5 (Large, 1954) divided by GDD greater than zero (GDD>0) were correlated with final grain yield. The in-season estimate of yield (INSEY) equation has been updated to included 30 site-years of data (Figure 1). This demonstrates that optical sensor readings collected near Feekes 5 can reliably predict final grain yield (solid line).

The relationship between yield data and sensor data can be described by an exponential curve. Standard regression techniques produce a prediction model that includes data from fields whose yields were adversely affected by events subsequent to the date of sensing that could not be predicted. Consequently, a model of actual grain yield may under predict or over predict potential grain yield at the sensing date. To correctly predict the potential yield, the model should be fitted to yields unaffected by adverse conditions from sensing to maturity. There is currently no established empirical method to determine how much the curve should be shifted. To approach the upper bound of the model, the constant ‘a’ within the exponential model ($y = ae^{bx}$) has been adjusted such that the number of observations above the curve was 32% of the total data points (Figure 1). This curve more realistically represents the yield potential achievable in rainfed winter wheat considering that post-sensing stresses (moisture, disease, etc.) from February to July could lower “observed yields.” Thus, yield potential plus one standard deviation (dashed line) is currently used in the algorithm for predicting yield potential.

Estimating the Responsiveness to Applied N

Identifying yield potential does not translate directly into an N recommendation. Consideration must also be given to the magnitude of field response to additional N. Johnson and Raun (2003) recognized that the response to applied N in the same field is entirely variable from one year to the next and independent of whether or not the previous year yields were high or low. To quantify this temporal variability they introduced a calculation known as the response index (RI). Initially RI was measured at harvest by comparing the yield of the check (0N) plot to that of a well fertilized plot which is explained by the equation:

$$RI_{Harvest} = (\text{yield of well-fertilized plot})/(\text{yield of check (0N) plot}) \qquad (1)$$

This, however, only indicated whether or not a response was noted at the end of the growing season which did not allow in-season adjustment. Subsequent work recognized that an in-season RI determined using an optical sensor at Feekes 5 could predict the RI measured at harvest using NDVI (Mullen et al., 2003).

$$RI_{NDVI} = (\text{NDVI of well-fertilized plot})/(\text{NDVI of check (0N) plot}) \qquad (2)$$

To determine RI in a practical sense, N fertilizer is applied to a strip extending across a field at a rate sufficient to assure that N is not limiting, but not excessive (Nitrogen Rich Strip). The use of a nitrogen rich strip (NRS), synonymous with reference strip, has also been utilized in corn N rate determination using a sufficiency concept (Varvel et al., 1997). Mid-season assessment of the NRS is made at the time of topdressing to quantify the response to applied N relative to a decreased field rate. In order to take advantage of the amount of N mineralized or contributed by the environment, preplant N for the field must be decreased (Johnson and Raun, 2003). This is an important point for utilization of an in-season N management strategy using optical sensors. If a large amount of N is applied preplant and an NRS is established, the likelihood of observing a response to the additional N (NRS) is small.

Yield potential for a specific field environment within a growing season obviously has a maximum value. To establish this maximum yield potential (YP_{Max}), sensor measurements are collected from the NRS. YP_{Max} is the maximum yield that could be expected within the most productive area in a field when N was not limiting for the year of measurement.

All the parameters are now known to compute an N recommendation. First, yield potential without additional N (YP_0) is computed using the yield prediction model (Figure 1).

$$YP_0 = 0.254exp^{(324.4*INSEY)} \qquad (3)$$

The yield potential attainable with additional N fertilizer (YP_N) is computed using the equation

$$YP_N = YP_0 * RI \qquad \text{Given that: } NDVI \geq 0.25 \text{ and } YP_N < YP_{Max} \qquad (4)$$

An NDVI value of 0.25 is considered a transition between bare soil and an appreciable wheat stand. Values less than 0.25, when measured at Feekes 5, have a crop yield potential so low that there is no appreciable benefit to N application. Figure 2 illustrates the response index theory of predicting crop yield increase. For the example presented, the hypothetical field has a YP_{Max} of 4 Mg ha^{-1}, an RI of 1.75, and GDD>0 of 100 (Figure 2). In this example, between NDVI = 0.25 and NDVI = 0.56 the crop benefits from additional N, and the potential yield increase is the product of RI and YP_0. Between NDVI = 0.56 and NDVI = 0.74, additional fertilizer can boost grain yield up to the maximum potential yield, YP_{Max}. Beyond NDVI = 0.74 there is no benefit for additional fertilizer N, because potential yields have reached the maximum for the field.

Based on the predicted values for YP_0 and YP_N, an N recommendation is computed using the equation

$$N_{rec} = 23.9 * (YP_N - YP_0)/eff \qquad \text{Given that: } 0.5 \leq eff \leq 0.7 \qquad (5)$$

where 23.9 is the percent N contained in wheat grain and *eff* is the efficiency factor for topdress N. The peak amount of N recommended using the previous field parameters (YP_{Max} = 4 Mg ha^{-1}, RI = 1.75, and GDD>0 = 100) is 69 kg ha^{-1} using an efficiency factor of 0.6 (Figure 3).

Using the RI algorithm reported, Raun et al. (2002) showed that winter wheat NUE was improved by more than 15% when N fertilization was based on INSEY calculated from optically sensed NDVI, determined for each 1m^2 area, and the response index when compared to traditional practices at uniform N rates. We are not aware of any biological basis to suggest that this approach would not be suitable in other cereal crops.

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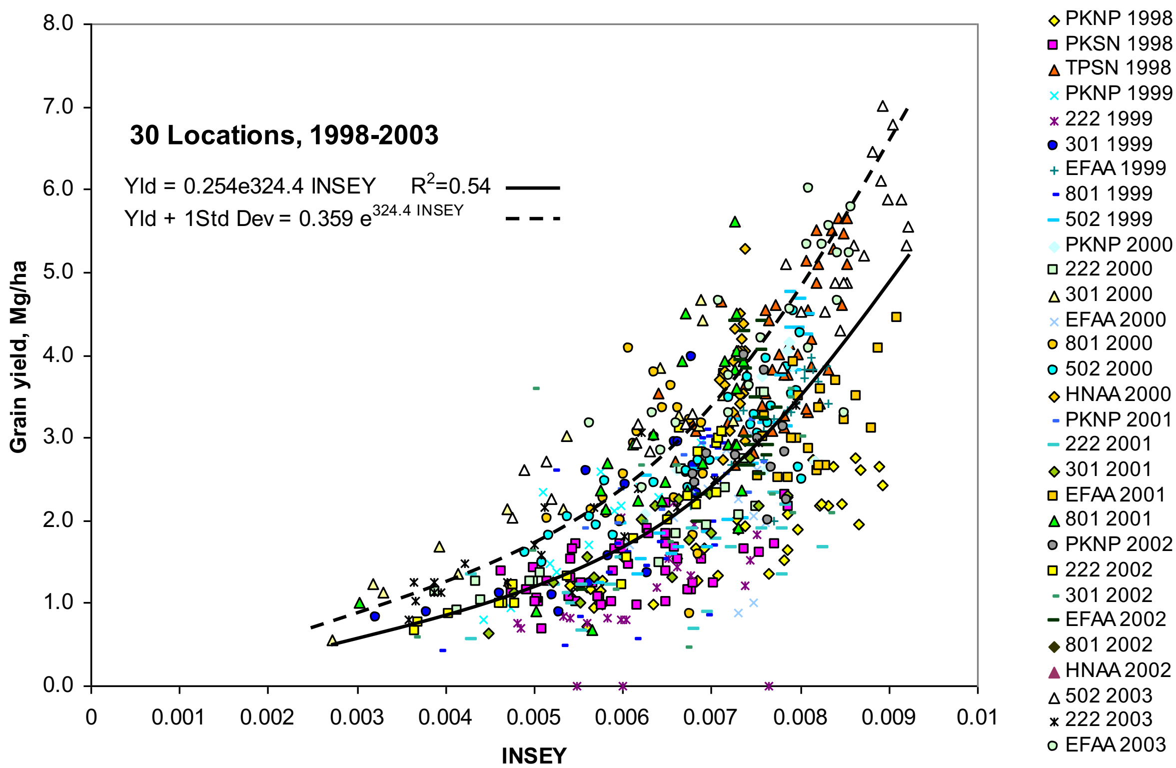

Figure 1. Relationship between observed wheat grain yield and the In Season Estimated Yield (INSEY) determined by dividing NDVI by the number of days from planting to sensing (days where growth was possible, or GDD > 0) at 30 locations from 1998 to 2003.

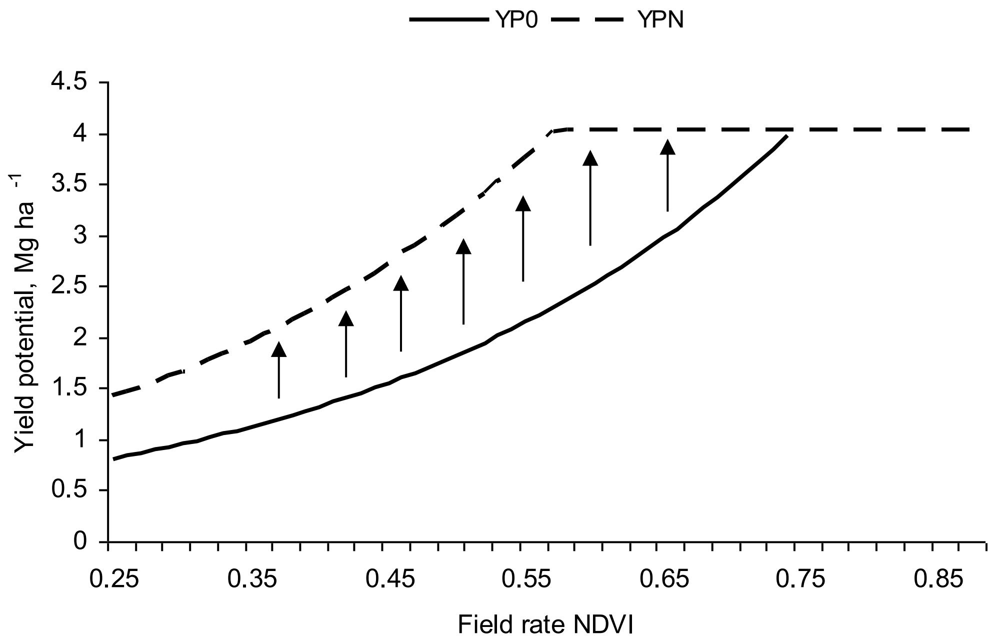

Figure 2. Change in potential yield of wheat with additional N fertilizer for an RI of 1.75, a maximum potential yield of 4.0 Mg ha^{-1} and 100 days after planting where GDD > 0.

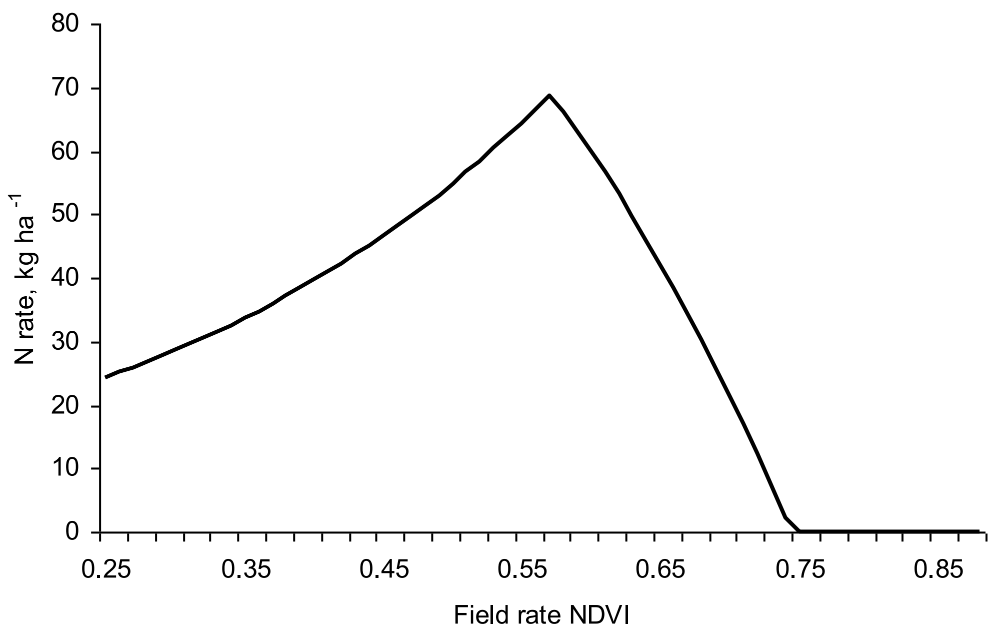

Figure 3. Recommend N rate for a range of NDVI (0.25 to 0.88) for an RI of 1.75, a maximum yield of 4 Mg ha^{-1}, and 100 days after planting where GDD > 0 (NDVI values below 0.25 do not receive N).