AN ENVIRONMENTAL ASSESSMENT OF SENSOR-BASED VARIABLE-RATE NITROGEN MANAGEMENT IN CORN

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Abstract

In order to address the problem of nitrate contamination of surface and ground waters, various methods have been used to try to account for spatial variability of N within agricultural fields. One approach to account for this variability and thereby reduce nitrate pollution is in-season site-specific N application according to economic optimal N rate (EONR). Recently, active crop canopy sensors have been tested for mid-season, on-the-go N fertilizer application in corn. This 2004 and 2005 study was conducted on 12 Missouri producer corn fields to (1) evaluate the relationship between EONR and active canopy sensor readings, and (2) evaluate the relationship between environmental measurements and EONR. Measurements included EONR, yield efficiency (YE), N fertilizer recovery efficiency (NFRE), and post-harvest soil inorganic N levels. In 2004, EONR was significantly related to active crop canopy sensor indices, but with regression model coefficients of determination (r^2) ≤ 0.35 for all sensor indices evaluated. As N rate approached EONR, both YE and NFRE declined, while post-harvest inorganic N levels increased. A relationship between EONR and the indices could not be established for 2005 data, primarily because of droughty conditions. These preliminary results show promise for using active-light reflectance sensors to achieve EONR and reduce N loss off fields.

Introduction

Agricultural producers constantly balance the competing needs of environmental stewardship and maximizing economic profit. Nitrogen (N) application is critical in crop production. Many producers apply uniform, whole-field N rates. However, because of a variety of factors, soil N levels and crop N needs vary between fields (Bundy and Andraski, 1995; Mamo et al., 2003; Schmitt and Randall, 1994) and within the same field (Malzer et al., 1996; Scharf et al., 2005). As a result of spatial and temporal variability of N supply and need, uniform application rates inevitably lead to under-fertilization of some areas of a field, while others receive a wasteful overabundance of N. This situation is accentuated in drier than average years when overall productivity is reduced and less N is taken up by plants.

One approach to account for this variability of N supply and need and thereby reduce nitrate pollution is in-season site-specific N application according to economic optimal N rate (EONR). Areas of a field where N is applied at less than EONR are unable to reach yield potential, and profitability is lost. Conversely, areas of a field where N is applied in excess of EONR reach yield potential but economic and environmental losses are incurred as a result of unused N in the soil. Many producers still see the reduced yield of under-application as outweighing the costs of unused applied N (Scharf et al., 2005), and therefore use "insurance" N applications to guard against reduced yield. Profitability for the producer will increase and environmental concerns will be minimized as fertilizer use efficiency increases (Malzer et al., 1996). The goal of variable-rate N application is to match inputs with crop needs site-specifically and thus increase N use efficiency.

Recently, active crop canopy sensors have been tested in corn to increase N fertilizer use efficiency through in-season, site-specific N application at EONR. Active crop canopy sensing is a ground-based form of remote sensing. Active crop canopy sensors use an LED (light emitting diode) light source to generate two wavelengths of light, one in the visible portion of the electromagnetic spectrum and one in the NIR. These wavelengths of light are then reflected off the crop and measured by a photodiode on the sensor. Passive reflectance sensors that rely on ambient sunlight are affected by environmental conditions such as clouds or sun angle. These changing conditions have minimal impact on active sensors. Recently, active canopy sensors have been used as part of an on-the-go fertilizer application system (Raun et al., 2002; Shanahan et al., 2003).

Active canopy reflectance technology is based on reflectance measurements discriminating plants with different color and/or biomass, relative to varying levels of N in the plant. This reflectance information is most often used to calculate a vegetation index which can then be incorporated into an N-rate algorithm. Prior research identified an appropriate algorithm for N application in wheat (Raun et al., 2002; Raun et al., 2005). Research is underway to determine efficient algorithms that incorporate reflectance measurements to calculate side-dress N application rates in corn. The goal of this research project was to provide an assessment of the environmental effects of using active crop canopy sensors on producers' cornfields in Missouri.

Objectives

Research objectives were:

1. Evaluate the relationship between EONR and active crop canopy sensor readings;
2. Examine the relationship between environmental measurements and EONR.

Materials and Methods

Research Locations

Research was conducted during the 2004 and 2005 growing seasons on eight producer corn fields in 2004 and five fields in 2005. Field locations were primarily in central Missouri, and were selected from three major corn-production soils of Missouri (river bottom, loess hills, and claypan). Because research was conducted on producer fields, cooperating producers selected the planting date, hybrid and planting population, and then prepared and planted each field with their own equipment. Fields were in rainfed production areas, except for one field, which received supplemental center-pivot irrigation when needed. Producer fields varied from 0.4 to 0.8 km in length.

Experimental Design and Treatments

Research plots for each treatment set were arranged in a randomized complete block design (RCBD). Each treatment set consisted of eight different N treatments. These varied from 0 to 235 kg N ha^{-1} on 34 kg N ha^{-1} increments. Experimental plot dimensions differed between the two years. In 2004, each research plot within a treatment set was 6 rows wide (4.5 m on 76 cm corn row spacing) by 15.2 m long. Treatment sets were two plots wide by four plots long. In 2005, research plots were 12 rows wide (9.1 m on 76 cm corn row spacing) by 30.5 m long. Treatment sets were four plots wide by two plots long. The number of treatment sets per field varied from 3 to 11, depending on the length of the field. N-rich reference areas were located on both sides of the treatment sets. N was applied to these areas at the time of crop emergence.

An AGCO Spra-Coupe (AGCO Corp., Duluth, GA) high-clearance applicator outfitted with reflectance sensors was used to apply N treatments. N treatments were applied at side-dress, which varied between V7 to V9 growth stage depending on the field. N was applied in the form of UAN (32% N), with an appropriate amount of urease inhibitor Agrotain, at rates of 0, 34, 67, 101, 134, 168, 202, and 235 kg N ha^{-1}. Fertilizer was not incorporated.

EONR Measurements and Calculation

In 2004, plots were hand-harvested from 6 m of the middle two rows of each plot. Stalk counts from the harvested area were taken to calculate plant population. In 2005, eight of the 12 rows of each plot were harvested with a Gleaner R42 combine (AGCO Corp., Duluth, GA) with a four row corn header. Plant population was collected with mechanical sensors on the combine header, as discussed by Sudduth et al. (2004). Yield data was collected with an Ag Leader Yield Monitor 2000 (Ag Leader Technology, Ames, IA) and data was cleaned using Yield Editor 1.02 (USDA-ARS, Columbia, MO). The center 18 m of each plot was used to calculate yield.

For all fields, a regression *F*-test ($\alpha = 0.05$) was first performed to determine the influence of N rate on field plant population. A regression *F*-test ($\alpha = 0.05$) was also used to assess whether plant population significantly affected yield. For all fields, there was no relationship found between N rate and plant population. In 2004 there was no relationship found between plant population and yield. In 2005, a population correction based on each field's mean population was used to adjust individual plot yield.

Once yield data had been cleaned and adjusted for population, a quadratic plateau model was fitted to data for each research field, and for each treatment set within each field to evaluate yield response to N application. Models of data sets with an *F*-test $p \leq 0.10$ were judged to be significant. EONR was determined based on a corn grain price of \$0.08 kg^{-1} (\$2 bu^{-1}) and N fertilizer cost of \$0.66 kg^{-1} (\$0.30 lb^{-1}). EONR was constrained to never exceed 235 kg N ha^{-1}, the highest N application rate.

Reflectance by Sensors

Active crop canopy sensor measurements were taken from treatment sets and N-rich reference areas on the same day N was applied to the treatment sets. The sensor used was the Holland Scientific Crop Circle (ACS-210), (Holland Scientific, Inc., Lincoln, NE). This sensor obtained reflectance data at 590 nm +/- 5.5 nm and 880 nm +/- 10 nm. Two sensors were mounted on the front of the applicator ~53 cm above rows 2 and 5 of a 6-row corn strip. Readings from the two rows were averaged.

The N-rich reference areas were adjacent to both sides of the research area. Average reflectance values for each treatment set were compared to reflectance values from the adjacent N-rich reference area. This comparison was accomplished using vegetation indices. One index evaluated was the visible relative to near-infrared ratio (Vis/NIR_{ratio}). This index related reflectance measurements from the N-rich reference area to reflectance measurements from the plot (or target) area through the following formulas:

$$Vis/NIR_{ratio} = [(Vis/NIR)_{Nref}] / [(Vis/NIR)_{target}] \qquad [1]$$

where "target" was the N rate treatment set area and "Nref" was the adjacent N-rich reference area. This resulted in an index which ranged from 0.5 to 1.0. As index values approached 1.0, the plot area reflectance measurements resembled reflectance measurements from the N-rich reference area. Index values for each treatment set were then related to EONR.

The relationship of soil EC and this index to EONR was evaluated for 2004 fields. EC data for each field was collected prior to crop establishment using a Veris soil EC mapping system (Veris Technologies Inc., Salina, KS).

Environmental Measurements

Three environmental measurements were used to account for N fertilizer that was applied to each plot. These included yield efficiency (YE), N fertilizer recovery efficiency (NFRE), and post-harvest soil profile inorganic N. Each was measured on N rate treatments and related to EONR. YE and NFRE were calculated by the following equations:

$$YE\ (\text{kg corn/kg N}) = (Y_i - Y_{\text{check plot}})/N_i \qquad [2]$$
$$NFRE = [(NR_i - NR_{\text{check plot}}) / N_i]100 \qquad [3]$$

where Y_i was plot yield (kg ha^{-1}), $Y_{\text{check plot}}$ was yield of a plot that did not receive N fertilizer (kg ha^{-1}), N_i was the N rate of the plot (kg ha^{-1}), NR_i was the N recovered from the plot (kg ha^{-1}), and $NR_{\text{check plot}}$ was the N recovered from a plot the did not receive N fertilizer (kg ha^{-1}).

For both years, post-harvest soil samples were taken to a depth of 120 cm from three different fields. Results were used to calculate residual soil profile inorganic (NO_3^- and NH_4^+) N levels, and related to the difference from EONR.

Results and Discussion

EONR Measurements and Calculation

Yield response models varied widely between and within each of the research fields in 2004. Corn production conditions were favorable in 2004 and resulted in high yields, and each field had significant ($\alpha = 0.05$) yield response models. Almost the opposite was true in 2005. In 2004, the field average r^2 value for the yield response models was 0.70. The r^2 value for the four 2005 fields varied from 0 to 0.59. This wide range in r^2 for 2005 fields was attributed to extremely dry conditions at essential times during the growing season. Drought stress resulted in poor growth and grain production, and an inability of plants to respond to differences between N treatments.

Yield response model results were incorporated into the EONR calculation. Between-field EONR calculations varied widely. EONR for the eight 2004 fields ranged from 86 to 222 kg N ha^{-1}. Variability of EONR within fields was similar to findings by Mamo et al. (2003) and Scharf et al. (2005). The range of EONR for 2004 fields was as narrow as 44 kg N ha^{-1} (CI04, Fig. 1a), and as wide as 131 kg N ha^{-1} (S04, Fig. 1a). For the two 2005 fields with significant yield response models, within-field EONR varied as much, if not more, than in 2004 fields.

Reflectance by Sensors

In 2004, data for the Vis/NIR_{ratio} index was fitted with a second-order significant (α = 0.05) polynomial (Figure 1a). Index values did not seem to vary according to the three different soil regions represented by these fields. Vis/NIR_{ratio} index was better able to distinguish extremes in soil variability within the same field. Generally, the index was able to grossly identify corn that needed less N (> 0.85 Vis/NIR_{ratio}). For this year of ideal growing conditions, sensor readings at side-dress growth stage were not sensitive to variation in EONR for lower ratio values (e.g. < 0.85 Vis/NIR_{ratio}). For Vis/NIR_{ratio} values between 0.85 and 1.0, the regression-predicted EONR decreased from about 160 to 90 kg ha^{-1}, respectively. For those fields with points < 0.85, the average producer N rate was 185 kg ha^{-1}. Because the indices are able to roughly distinguish areas of a field which required high amounts of N from areas of a field which required less N, the Vis/NIR_{ratio} index might be a useful tool for determining N management zones within fields based on sensor measurements. Such an N management strategy would likely reduce NO_3-N leaching potential, as discussed by Delgado et al. (2005).

In 2005, only three treatment sets had significant EONR values. Due to a limited number of 2005 treatment sets where EONR could be found, a meaningful relationship could not be established between EONR and Vis/NIR_{ratio} index.

The relationship for predicting EONR using the Vis/NIR_{ratio} index and soil EC was evaluated for 2004 fields (Figure 1b). Although EC alone was not a significant variable, the interaction of Vis/NIR_{ratio} and EC was significant (α = 0.05). The addition of EC better explained EONR results in the field (r^2 = 0.47) compared to the relationship between index values and EONR alone ($r^2 \leq 0.35$). These results suggest that soil EC measurements have potential for establishing N management zones within or between fields, similar to findings by Kitchen et al. (2005).

Environmental Measurements

Yield Efficiency at EONR was not the same between fields in 2004, ranging from 19-47 kg grain $(kg\ N)^{-1}$ (Figure 2). This wide range of variability in YE at EONR could possibly be linked to soil characteristics at each of the fields. However, even more importantly, producer management practices could have contributed to this observed variability through type of tillage used, selected corn hybrid, or past N management practices, among other things.

In 2005 the two fields with determinable EONR showed a trend similar to 2004 fields in relation to YE. As N rate increased, YE trended downward. Generally, once N rate matched EONR, YE decreased at a slower rate due to the plant having sufficient amounts of N for its vegetative and reproductive needs. Most fields had at least one treatment set where YE increased between 34 and 68 kg N ha^{-1}, before a decreasing trend. These observations of N application could be related to a "soil priming" effect with N fertilizer application (Leon et al., 1995).

Similar to YE, NFRE declined as N rate approached EONR (Figure 2). NFRE at EONR ranged from 35 to 46%. This value was higher than estimates of the world average NFRE (33-37%) for cereal crops (Cassman et al., 2002; Raun et al., 2002).

Profile inorganic N levels were not uniform between fields. Averaged across all treatment sets within a field, profile inorganic N at EONR ranged from 36 to 105 kg ha^{-1} for the three fields sampled in 2004 (Figure 2). Profile inorganic N levels were not always similar between treatment sets within fields. Overall, profile inorganic N levels increased as N rate increased both within- and between fields. These results suggest that fertilizing at EONR would potentially reduce N loss from crop production systems, thereby reducing detrimental effects of N fertilizer to the environment.

Conclusions

The objectives of this research project were to evaluate the relationship between active crop canopy sensor measurements and EONR, and relate EONR to YE, NFRE, and post-harvest soil inorganic N levels. EONR was at the center of this research project because it is the amount of N producers are trying to apply to achieve maximum profitability. Through a vegetation index approach, this research showed that EONR and active crop canopy sensors are related. N application at EONR determined from sensor measurements could reduce N loss to the environment.

The conclusions of this study were:

1. EONR was highly variable within and between corn fields.
2. EONR was greatly affected by yearly climate conditions. As a result of favorable growing conditions in 2004, EONR could be calculated for all fields and nearly all treatment sets. In contrast, nearly the opposite was observed in 2005 due to droughty conditions.
3. Because the sensor index, in conjunction with soil EC, was able to separate low and high EONR values, further research might involve sensors in the development of N management zones within fields.
4. As a result of inconclusive data results from droughty conditions in 2005, continued research in this area would be beneficial to explore the relationship between EONR, soil EC, and sensor indices, and between EONR and environmental measurements.

Active crop canopy sensors show promise to achieve EONR, thereby increasing YE and NFRE, and reducing N loss off fields. N application at EONR would alter current producer N rates, resulting in increased profitability for producers, and an overall positive effect on the environment.

References

Bundy, L.G., and T.W. Andraski. 1995. Soil yield potential effects on performance of soil nitrate tests. J. Prod. Agric. 8:561-568.

Cassman, K.G., A. Dobermann, and D.T. Walters. 2002. Agroecosystems, nitrogen-use efficiency, and nitrogen management. Ambio 31:132-140.

Delgado, J.A., R. Khosla, W.C. Bausch, D.G. Westfall, and D.J. Inman. 2005. Nitrogen fertilizer management based on site-specific management zones reduces potential for nitrate leaching. J. Soil Water Cons. 60:402-410.

Kitchen, N.R., K.A. Sudduth, D.B. Myers, S.T. Drummond, and S.Y. Hong. 2005. Delineating productivity zones on claypan soil fields using apparent soil electrical conductivity. Comp. Elect. Agric. 46:285-308.

Leon, M., P. Laine, A. Ourry, and J. Boucaud. 1995. Increased uptake of native soil nitrogen by roots of *Lolium multiflorum* Lam. after nitrogen fertilization is explained by a stimulation of the uptake process itself. Plant and Soil 173:197-203.

Malzer, G.L., P.J. Copeland, J.G. Davis, J.A. Lamb, and P.C. Robert. 1996. Spatial variability of profitability in site-specific N management. pp. 967-975. *In* P.C. Robert, R.H. Rust, and W.H. Larson (eds.) Proc. of 3rd Int. Conf. on Prec. Ag. 23-26 June 1996, Minneapolis, MN. ASA, CSSA, and SSSA, Madison, WI.

Mamo, M., G.L. Malzer, D.J. Mulla, D.R. Huggins, and J. Strock. 2003. Spatial and temporal variation in economically optimum nitrogen rate for corn. Agron. J. 95:958-964.

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, R.W. Mullen, K.W. Freeman, W.E. Thomason, and E.V. Lukina. 2002. Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. Agron. J. 94:815-820.

Raun, W.R., J.B. Solie, M.L. Stone, K.L. Martin, K.W. Freeman, R.W. Mullen, H. Zhang, J.S. Schepers, and G.V. Johnson. 2005. Optical sensor-based algorithm for crop nitrogen fertilization. Comm. Soil Sci. Plant Anal. 36:2759-2781.

Scharf, P.C., N.R. Kitchen, K.A. Sudduth, J.G. Davis, V.C. Hubbard, and J.A. Lory. 2005. Field-scale variability in optimal nitrogen fertilizer rate for corn. Agron. J. 97:452-461.

Schmitt, M.A., and G.W. Randall. 1994. Developing a soil nitrogen test for improved recommendations for corn. J. Prod. Agric. 7:328-334.

Shanahan, J.F., K.H. Holland, J.S. Schepers, D.D. Francis, M.R. Schlemmer, and R. Caldwell. 2003. Use of a crop canopy reflectance sensor to assess corn leaf chlorophyll content. *In* Digital imaging and spectral techniques: Applications to precision agriculture and crop physiology. ASA Special Pub. 66. ASA, CSSA, SSSA, Madison, WI.

Sudduth, K.A., S.J. Birrell, G.A. Bollero, D.G. Bullock, J.W. Hummel, and N.R. Kitchen. 2004. Site-specific relationships between corn population and yield. *In* D.J. Mulla (ed.) Proc. of 7th Int. Conf. on Prec. Ag. 25-28 July 2004, Minneapolis, MN. ASA, CSSA, SSSA, Madison, WI.

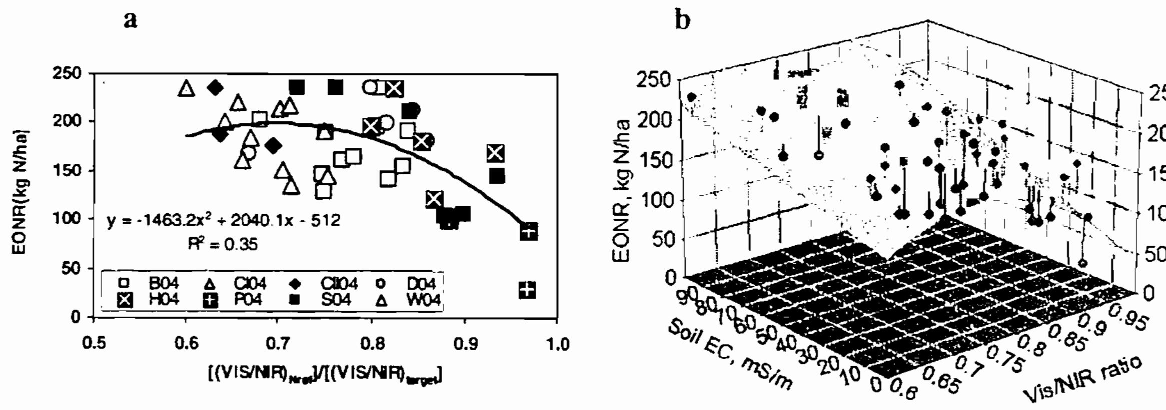

Figure 1: (a) EONR related to Vis/NIR$_{ratio}$ index based on active crop canopy measurements. (b) EONR relationship to soil EC and Vis/NIR$_{ratio}$ index.

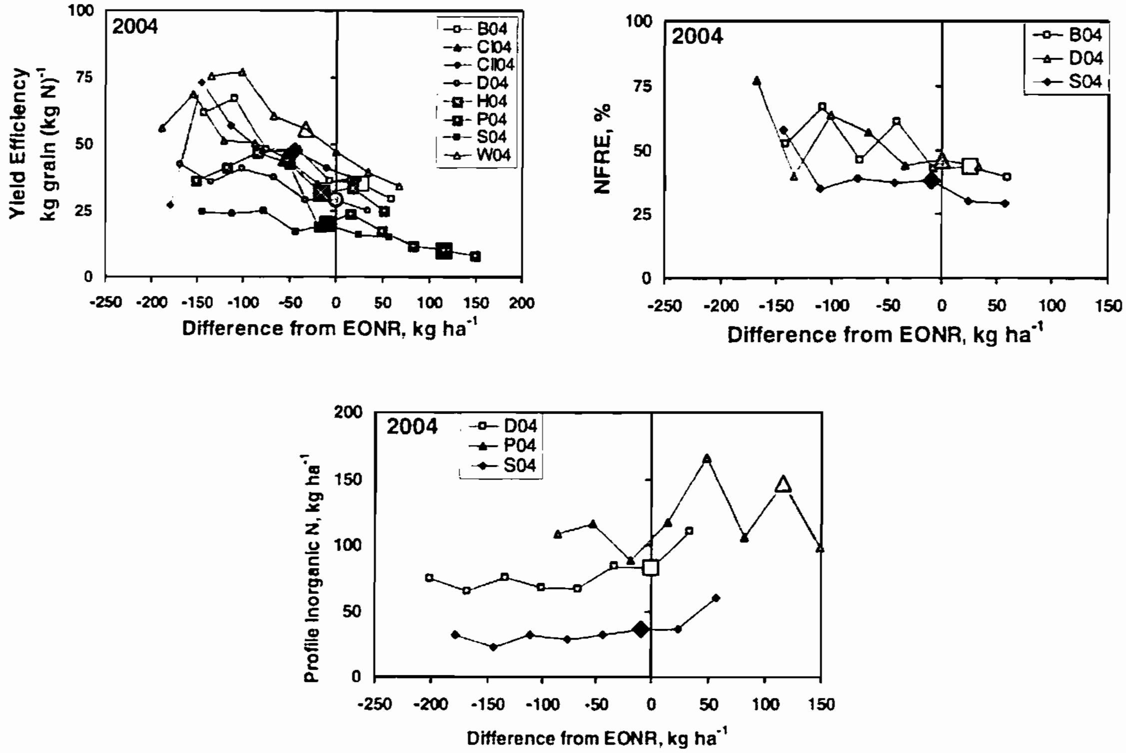

Figure 2: Difference from EONR related to environmental measurements YE, NFRE, and profile inorganic N for 2004 fields. Producer N rate at planting for each field indicated by enlarged symbol on each trendline.

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