Agri. & Biosys. Eng. Vol. 7(1):18-26(2006)

On-the-go Nitrogen Sensing and Fertilizer Control for Site-specific Crop Management

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Abstract: In-field site-specific nitrogen (N) management increases crop yield, reduces N application to minimize the risk of nitrate contamination of ground water, and thus reduces farming cost. Real-time N sensing and fertilization is required for efficient N management. An 'on-the-go' site-specific N management system was developed and evaluated for the supplemental N application to corn (*Zea mays* L.). This real-time N sensing and fertilization system monitored and assessed N fertilization needs using a vision-based spectral sensor and controlled the appropriate variable N rate according to N deficiency level estimated from spectral signature of crop canopies. Sensor inputs included ambient illumination, camera parameters, and image histogram of three spectral regions (red, green, and near-infrared).

The real-time sensor-based supplemental N treatment improved crop N status and increased yield over most plots. The largest yield increase was achieved in plots with low initial N treatment combined with supplemental variable-rate application. Yield data for plots where N was applied the latest in the season resulted in a reduced impact on supplemental N. For plots with no supplemental N application, yield increased gradually with initial N treatment, but any N application more than 101 kg/ha had minimal impact on yield.

Keywords: Nitrogen management, Fertilization, Sprayer, Precision agriculture, Real-time control

Introduction

Nitrogen (N) management is critical for corn production in the Midwest. Nitrogen is an essential nutrient required for plant growth and a major component of the chlorophyll molecule that enhances photosynthesis (Tracy *et al.*, 1992). Lack of N and chlorophyll means that plants cannot utilize sunlight as an energy source to carry on essential functions such as nutrient uptake (Borhan and Panigrahi, 1999). Fertilizer N is relatively inexpensive and deficiency in N application can result in substantial yield reductions. Thus, producers tend to apply excessive N to minimize the risk in deficiency.

However, excessive N fertilizer leaching into the groundwater creates serious environmental problems and has been linked to hypoxia problems in the Gulf of Mexico. Walker *et al.* (1997) pointed out that 39-89 kg/ha of excess N was applied during 1993-95 in East Central Illinois. The U.S. Environmental Protection Agency (1998) reported that nutrients were one of the leading causes for contamination in the waterways. Nitrogen levels in many regions are higher than the drinking water standard. Thus, there is an opportunity for a system that can assess plant N deficiency and fertilize only the required N throughout the growing season to enable producers to reach their production goal, while maintaining environmental quality through reduced fertilization.

Site-specific N management has potential benefit to improve input efficiency, output profitability, and environmental protection. Conditions that affect crop yield are not uniform within fields, and thus do not provide optimum efficiency or profitability under uniform N application practices that are used in conventional crop management. A practice of ite-specific N management would adopt variable rate N application within fields in response to plant needs.

Soil and yield mapping have been used to recommend variable amount of fertilizer application in crop production. However, both of them are restricted by the time required to obtain results, and their utility is bounded by the year in which they are generated (Stone *et al.*, 1996). Sawyer (1994) indicated that there were various factors that limit the application of map-based variable rate technology. These include cost of implementation (sampling, mapping, equipment, and personnel), lack of expected increase in crop yield, and lack of input savings.

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A number of papers have been published to report the N assessment of corn crops (Lee and Searcy, 2000; Bausch and Duke, 1996; Ma *et al.*, 1996; Blackmer *et al.*, 1994), but no extensive research has been conducted to develop a real-time sensing and fertilizing system. Heege and Reusch (1996) introduced a concept of 'on-the-go' system of site-specific management which directly assesses N deficiency level and sends spray control of N fertilizer. Heege and Thiessen (2002) discussed more about the sensor-controlled fertilizing system in their development of an optical sensor to assess N based on red-edge inflection point but did not include performance and yield evaluation of the system, rather focused on optical sensing systems. Hydro Agri (2003) developed a commercial on-the-go system, called 'Hydro N sensor', which determines the crop nitrogen demand by measuring the crop reflectance and sends a signal to the sprayer rate controller. But the system shows limitations: side-view-only sensing which generates erroneous application rate in the middle zone due to unmonitored signals and the spectroradiometers which suffer from the background noise effects from soil and crop shadows.

The objectives of this study were to provide extensive discussion on the conceptual structure of the sensor-controlled fertilizing system and evaluate the performance of real-time crop sensing and fertilization associated with a variable rate application system. In the remainder of the paper, a field crop imaging sensor and algorithm details are described for crop sensing and sprayer control. Results are presented from an experimental field application of N fertilization.

Materials and Methods

Conventional soil or plant tissue sampling measurements in a contact mode have been replaced by remote sensing techniques that make nondestructive measurements at some distance from the crop environment. A non-contact in-field sensor for plant N content was developed by Kim et al. (2000), using a multi-spectral imaging sensor (MSIS). The MSIS system was incorporated into a variable rate application system developed by Han et al. (2000).

A conceptual picture of the system is illustrated in Figure 1. A vision-based spectral sensor measures crop canopy reflectance from a nadir view under natural ambient illumination. An illumination sensor collects solar irradiance to compensate for ambient illumination variability. Reflectance data is processed to determine N status, which is then associated with a geo-referenced location obtained by a global positional system (GPS) receiver. A variable rate application system was installed on a sprayer to apply liquid N fertilizer on maize. The spectral N sensor and application software system enables a fertilizer controller to apply only the required N on a specific part of the field according to detected crop N deficiency levels. The system continuously captures crop images while moving through the field, processes each image to estimate N status, and applies site-specific N fertilizer.

1. Hardware Design

The crop N sensor was a ground-based remote sensor and consisted of a MSIS (a custom-developed imaging sensor, Cohu Inc., Poway, CA), ambient illumination (AI) sensor (SKR1850A 4-channel, Skye Instruments Ltd., Powys, UK), portable computer (PAC 586, Dolch Computer Systems, Inc., Fremont, CA), and differential GPS (Case IH AFS Universal Receiver, CNH Global N.V., Racine, WI). The MSIS was a custom-developed three charge coupled devices (3-CCD) camera with three video channels of green (G), red (R), and near infrared (NIR) with center wavelengths at 550 nm, 650 nm, and 800 nm, respectively, and bandwidth of approximately 100 nm for each channel. The AI sensor had also G, R, and NIR channels at the same wavelengths as the MSIS. All equipments were mounted on a research sprayer platform (Tyler Patriot, CNH Global N.V., Racine, WI) shown in Figure 2.

2. Nitrogen Assessment

The schematic layout of the field crop sensing system is illustrated in Figure 3. A crop image was captured by the MSIS. The AI sensor recorded ambient illumination. To compensate for the image intensity changes affected by varying illumination, the gain and exposure were dynamically adjusted by a fuzzy logic controller so as to position the average

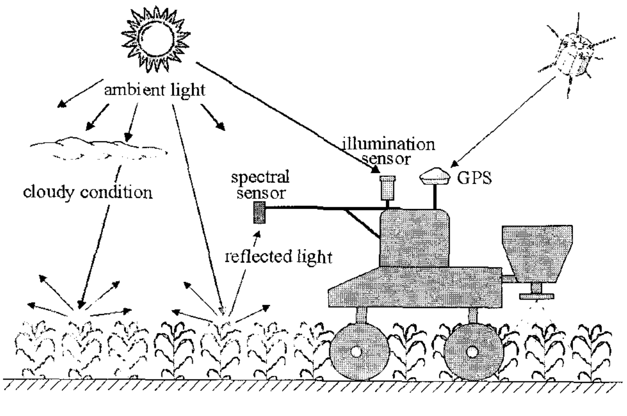

Fig. 1 Conceptual picture of N sensor-based real-time fertilization system; GPS, illumination sensor, and spectral sensor.

gray-level distribution for each of the three channels (R, G, and NIR) at the center of the range. After image convergence was reached with the control system, the image was segmented to remove non-vegetation components (typically, soil, and shadow pixels). Finally, the N application decision was made based on information given by the system and a spray control output was sent to a sprayer controller.

The reflectance response F for the MSIS system was developed based on solar energy transformation. It is a function of average gray-level value L, ambient illumination A, exposure E, gain g, and calibration coefficients c_1 and c_2 as following (Kim, 2002):

$$F_j = c_{1j} \frac{L_j}{A_j \times E_j \times 10^{c_{2j} \times g_j}} \tag{1}$$

where j is a spectral waveband of R, G, or NIR. The estimated reflectance responses in three spectral regions were used to calculate N sufficiency index NSI using a normalized difference vegetative index $NDVI$ as following:

$$NSI = \frac{NDVI_t}{NDVI_r}, \quad NDVI = \frac{NIR - R}{NIR + R} \tag{2}$$

$NDVI_t$ and $NDVI_r$ were obtained in a testing plot and in a reference healthy plot, respectively.

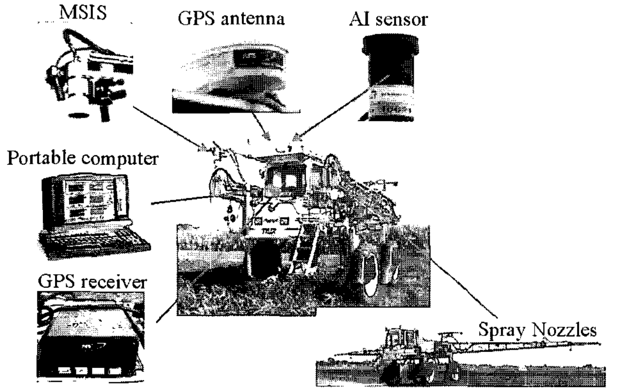

Fig. 2 Tyler Patriot sprayer platform for crop N sensing and fertilization system with main hardware components.

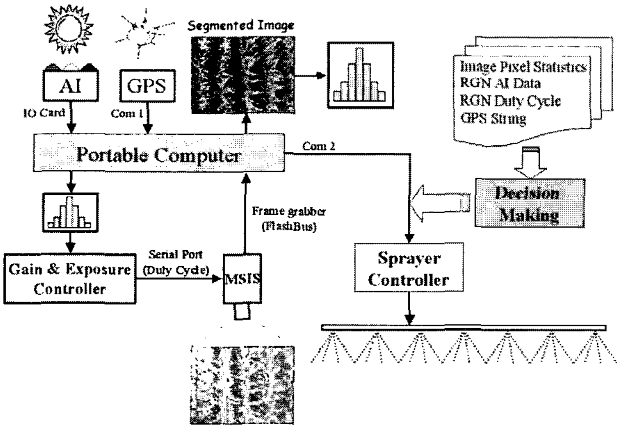

Fig. 3 Schematic layout of the crop N sensing system.

3. Variable Rate Application

The sprayer had a 22.9 m boom equipped with 25 drop nozzles. Individual spray nozzles were controlled by application software with two controllers: one for system pressure control and the other for flow rate control (Figure 4). The pressure setting affects the flow rate capacity and was kept constant during the operation. The flow rate controller was a pulse width modulation (PWM) driver that provides square wave signals to the solenoid valves. Each PWM channel had 16 bit resolution and provided a duty cycle from 0 to 100% with 1% increment. Application software included adjustments for transport delay in flow rate response time of the solenoid-operated valve. The sprayer was able to adjust spray rate continuously and apply in nearly continuous increments throughout the variable rate treatment.

The calculation of variable N rate was based on the N deficiency level detected by the MSIS sensor. The detected N deficiency was used to estimate a corresponding value of a chlorophyll meter (SPAD 502, Minolta Co., Japan), called a SPAD meter, that measures light transmittance of two light emitting diodes through a plant canopy. The calculation of a $SPAD$ is based on optical density difference at two wavelengths of R at 650 nm and NIR at 940 nm as follows:

$$SPAD = K \times \log_{10}\left(\frac{NIR_t \times NIR_o}{R_t \times R_o}\right) \tag{3}$$

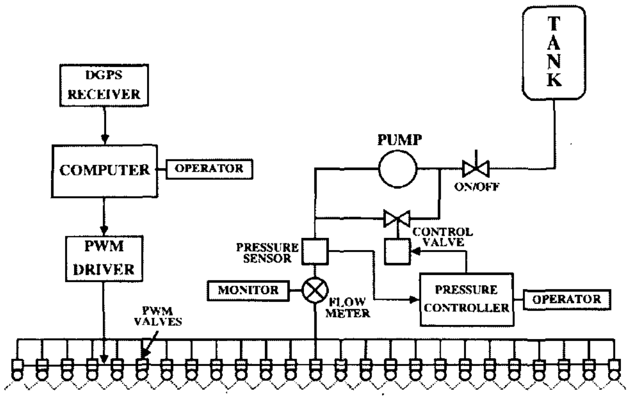

Fig. 4 Application controllers and their integration into the system (Han et al., 2000).

where K is a calibration constant, NIRt and Rt are the transmittance of NIR and R wavelength, and NIRo and Ro are the light power of NIR and R wavelength, respectively. The SPAD value for a plant canopy typically ranges from 0 to 60, where higher values indicate higher chlorophyll content.

With the estimated SPAD value and other factors such as target yield, manure applied to the field, leaf stage of plants at time of application, and reference plot, the variable N fertilizer application rate was determined using N recommendation Nrec proposed by Francis and Piekielek (1999):

$$Nrec = 280 + Yf - Mf - Sf - Pf \tag{4}$$

where Y_f is the yield factor (target yield × 0.9), M_f is the manure factor (manure value × relative SPAD reading), S_f is the leaf stage factor (19 × leaf stage of crop × relative SPAD reading), and P_f is the reference plot factor (4 × average reference area SPAD reading). The field SPAD reading $SPAD_{estimate}$ was estimated by the MSIS sensor in reflectance response to the levels of applied nitrogen as follows:

$$SPAD_{estimate} = 189.577 + 629.9 \times NSI_R - 156.2 \times NSI_G - 339.8 \times NSI_R^2 + 108.7 \times NSI_G^2 \tag{5}$$

where NSI_R and NSI_G are N sufficiency indices in red and green channels, respectively, described in Eq. (2). It is noted that NSI_G drives $NDVI_G$ that is not actually $NDVI$ value since it uses green channel instead of red channel value but used for expression only. The calculation of the variable N rate included values for the following four factors inserted into Eq. (4): the target yield of 10 ton/ha, the manure value of 0.75 (for no manure applied since harvesting the previous crop), reference SPAD value of 58, and leaf stage crop of 9.

4. System Integration

An overall flowchart of integrated system operation is illustrated in Figure 5. The MSIS characterized the spectral signature of target crops and estimated N deficiency through a reflectance model. A corresponding value of a SPAD chlorophyll meter was predicted from the N deficiency. Once the N amount was determined, a spray nozzle control was activated by the application controllers, converting target application rate into a duty cycle. The cycle time depended on image processing to compensate ambient illumination change and average update rate was about 1.5 s, which allowed the vehicle speed up to 2 m/s with image field of view of 4 m in horizontal and 3 m vertical dimension.

The distance between the N sensor and spray nozzles was compensated by a time delay based on the vehicle speed. With the fixed distance as shown in Figure 6, the time delay was calculated with the distance (7.4 m) divided by the travel speed. The time delay was updated every sampling, because it was affected by a travel speed. The geo-positional information from the GPS was also used to provide the position in deriving a field map.

The control system varied N application rate based on N deficiency levels detected by the MSIS. Mapping geographic information system (GIS) was used to compare SPAD and MSIS-estimated SPAD response in the field. The crop harvested from the treated and untreated rows was compared to assess the effects of N application on yield.

5. Experimental plot design

An experimental field was prepared and planted with

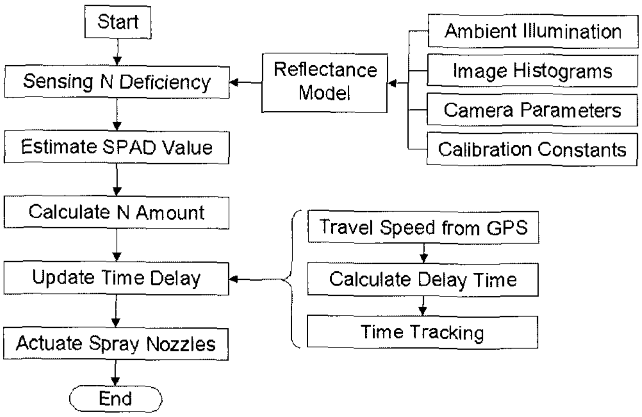

Fig. 5 Flowchart for a real-time sensing and fertilization system.

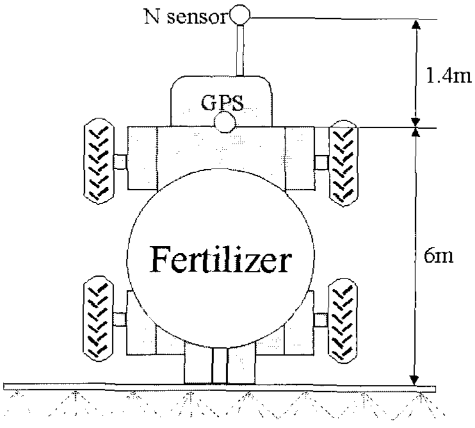

Fig. 6 Dimensions of the hardware arrangement.

corn (Pioneer) on April 26, 2001. Each plot had eight rows of 150 m long with 76.2 cm row spacing. Each plot consisted of six subplots of 25 m long and 6 m wide and was replicated to generate six experimental plots (plot 11-16) as shown in Table 1. To establish varying levels of N content, six different N treatments (0, 34, 67, 101, 135, and 224 kg/ha) were randomly applied on individual plots on May 8, 2001 and repeated following a randomized design.

Nitrogen fertilization was applied in the form of N solution dripped on the soil surface. Additional N treatment using the MSIS-based fertilization system was applied on two plots (plots 12 and 13). The weight data were converted into yield Y as follows:

$$Y=\frac{w}{s\times l} \tag{6}$$

where s is the swath (3 m) and l is the length (22 m) of each subplot and w is the weight measured by harvesting only middle four rows on each eight-row subplot to eliminate boundary effects between adjacent subplots.

Results and Discussion

Additional N using the MSIS-based fertilization system was applied on two of the six experimental plots: plot 13 on July 6 and plot 12 on July 20, 2001. MSIS mapping on the experimental field took place at three times: on June 27, July 10, and July 23, 2001. Data analysis included consideration of time delay for N uptake by plants, because the side-dressed N takes time for plant to uptake. Accordingly, the N applied on July 20 was not observed in the mapping data on July 23. For the same reason, the N applied on July 6 was excluded from the mapping data on July 10. Thus, the data obtained up to July 23 were analyzed by including N fertilization applied on July 6.

Statistical analysis for the experimental plot design was conducted to see if there was significant difference among six levels of initial N and no significant difference among four replications. Eight SPAD readings were measured around the middle area of each subplot on June 27. An analysis of variance (ANOVA) indicated that SPAD readings were significantly affected by N treatment at the 95% confidence level, as the hypothesis of no difference among six replications was rejected (Table 2). The ANOVA for four replicated plots resulted in no difference among them in all six different N treatments at the 95% confidence level, since the hypothesis of no difference among four replications was accepted (Table 3).

Crop health status was assessed by the variations of SPAD values between crop without additional fertilization and crop with the MSIS-based additional fertilization as shown in Figure 7. Figures 7 (a) and 7 (b) illustrate the SPAD comparisons through the growing season of a plot with 34 kg/ha applied N and 135 kg/ha applied N, respectively.

The plot with 34 kg/ha N treatment without additional fertilization shows a sharp decrease in SPAD value as the growing season progressed (Figure 7 (a)). This indicates plant stress is increasing, since the small amount of pre-applied N is quickly utilized by the plants. A similar phenomenon was found in the plot with 135 kg/ha N treatment without additional fertilization, showing that the SPAD value was dropped after the available N was consumed by the plants

Table 1 Experimental corn field, planted on April 26 and initial N kg/ha treated on May 8, 2001 (shaded two plots were used for sensor-based supplemental fertilization)

	1	2	3	4	5	6	1	2	3	4	5	6	
plot 15	0	34	67	101	135	224	135	101	0	67	34	224	plot 14
plot 16	224	135	101	67	34	0	34	135	67	101	224	0	plot 13
							224	101	0	67	34	135	plot 12
							135	0	67	34	101	224	plot 11

25 m

6 m

150 m ——— 150 m

Table 2 ANOVA table for plots with six different N treatments (df: degree of freedom, SS: sum of square, MS: mean square, F_α: critical value, α: significance level)

Source	df	*SS*	*MS*=*SS*/df	*F*-statistics	$F_{0.05}$
Treatment	5	65.15	13.03	4.54	2.53
Error	30	86.13	2.87		
Total	35	151.27			

Table 3 F-statistics of ANOVA test for four replicated plots in six different N treatments (N: nitrogen in kg/ha, df: degree of freedom)

Source	df	F-statistics						$F_{0.05}$
		N=0	N=34	N=67	N=101	N=135	N=224	
Treatment	3	1.17	2.61	1.36	2.62	2.50	1.91	2.95
Error	28							
Total	31							

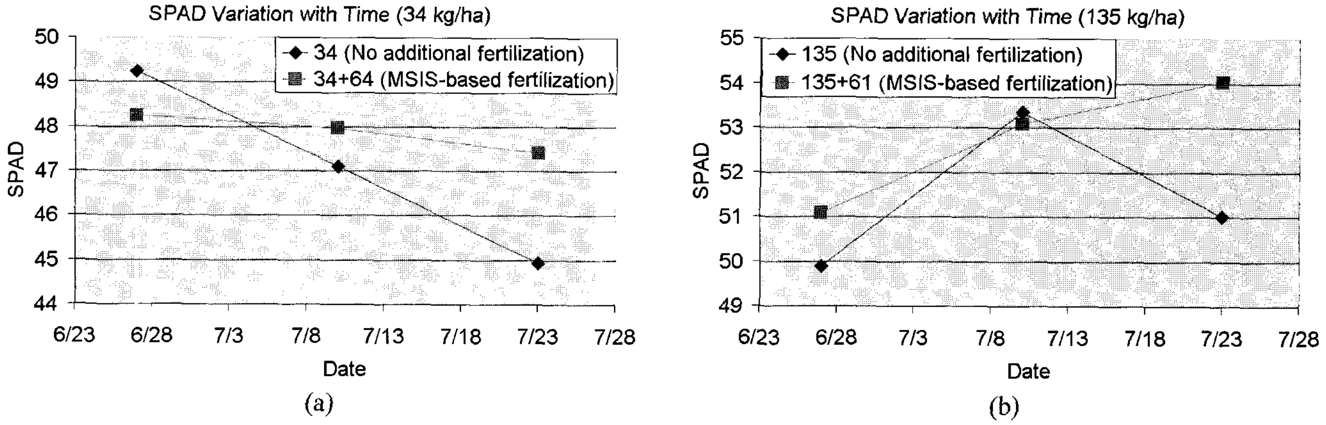

Fig. 7 Comparison of SPAD variations through the growing season between plot without additional fertilization and plot with the MSIS-based additional fertilization: (a) plot with 34 kg/ha applied N; (b) plot with 135 kg/ha applied N.

in the middle of July (Figure 7 (b)). On the other hand, in crops managed with the MSIS-based system, additional fertilization maintained the plant response in certain range of SPAD values (Figure 7 (a)) or improved the SPAD value (Figure 7 (b)). This indicates that the additional N, 64 kg/ha in Figure 7 (a) and 61 kg/ha on the plots in Figure 7 (b), applied based on N stress level estimated by an MSIS system provided supplemental N required to sustain plants through the growing season.

An additional evaluation was made of yield for comparison between plots without additional fertilization and plots with the MSIS-based fertilization. Corn was harvested on October 20, 2001, providing weight measurements. Figure 8 illustrates the yield comparison of the harvested plots as a function of the initial N treatments. Each data point in Figure 8 reflects the yield of an individual subplot with six different N treatments. The data points of the plots with no additional fertilization were an average of the four replicated subplots, while those of the plots with the MSIS-based fertilization were one value per subplot. The yield from two plots (plot 13 and plot 12) was obtained with the MSIS-based additional fertilization. The subplot with no N treatment showed the least yield, approximately 6.9 ton/ha, while the subplot with 135 kg/ha of N produced the highest yield, approximately 9.4 ton/ha.

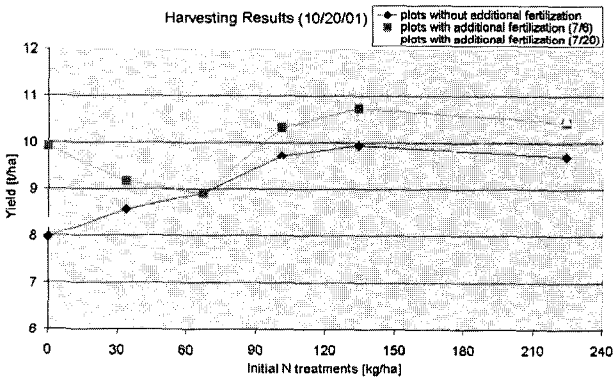

Fig. 8 Yield comparison between plot without additional fertilization and plot with the MSIS-based additional fertilization.

Yield improvement with variable rate application is tabulated in Table 4. Average yield increased from 9.1 ton/ha to 9.9 ton/ha. It is more meaningful to compare the yield on an individual subplot rather than whole plots, because the yield improvement was contributed by plots with small amounts of initial N treatment. For example, the yield improvement from the plot with no initial N treatment was increased from 8.0 ton/ha to 9.9 ton/ha. The yield increase was 1.9, 0.6, and 0.6 ton/ha on the plots with

Table 4 Yield data from three different plots

Initial N [kg/ha]	Yield [ton/ha] (with no additional N)	Yield [ton/ha] on plot 13 (additional N on 7/6)	Yield [ton/ha] on plot 12 (additional N on7/20)
0	8.0	9.9	8.3
34	8.6	9.2	7.4
67	8.9	8.9	9.5
101	9.7	10.3	9.6
135	9.9	10.7	9.3
224	9.7	10.4	10.5
Average	9.1	9.9	9.1

Table 5 Supplemental N treatments (△N) and yield increases (△Y) from the MSIS-based fertilization on the plots, plot 13 applied on July 6 and plot 12 on July 20

Initial N [kg/ha]	△N [kg/ha] (plot 13)	△Y [ton/ha] (plot 13)	△N [kg/ha] (plot 12)	△Y [ton/ha] (plot 12)
0	64	1.9	49	0.3
34	61	0.6	52	-1.2
67	59	0	53	0.6
101	57	0.6	53	-0.1
135	57	0.8	53	-0.7
224	61	0.7	50	0.8
Average	59.8	0.78	51.7	-0.05

supplemental N over initial N treatment 0, 34, and 101 kg/ha, respectively. Plots with large amounts of initial N treatment also had yield improvements of 0.8 and 0.7 ton/ha on the plots with supplemental N over initial N treatment 135 and 224 kg/ha, respectively (Table 4).

Plot 12 with additional N applied on June 20 resulted in mixed improvement in yield data (Figure 8). Further analysis of the experiment determined that leaf stage of crop in Eq. (4) for the N recommendations was incorrectly set to V9 (about 9 leaves) (Ritchie *et al.*, 1986) from the earlier experiment. This generated less amount of supplemental N. For example, the leaf stage of V10 (about 10 leaves) (Ritchie *et al.*, 1986) would have applied 17.6 kg/ha less, when assuming field SPAD reading of 48. Another factor to be considered was the reference area SPAD reading. Assuming a minor variation of SPAD value on healthy crops, the supplemental fertilization used a fixed value (58) for the reference SPAD value. This assumption was not valid, because the plant health condition varied over time. Such variation was enough to affect the calculation of the N recommendations. The misuse of these two factors created inadequate amount of the supplemental N as shown in Table 5, resulting in only small variation of the supplemental N amount: from 57 kg/ha to 64 kg/ha in plot 13 and from 49 kg/ha to 53 kg/ha in plot 12. Such small range of additional N amount provided by the predicted *N recommendation* (Eq. (4)) was not enough to differentiate stress levels and needed further experimental study.

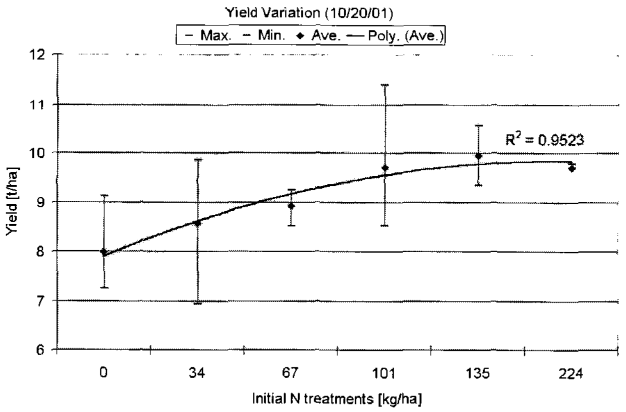

Fig. 9 Yield variation from four-replicated corn plots along with initial N treatments.

Average yield improvement was 0.78 ton/ha with additional 59.8 kg/ha N treatments. The yield improvement was found over all plots except the subplot with 67 kg/ha initial N treatment in which some measurement error was suspected. For individual plots, the highest yield increase was obtained on the plot with no initial N treatment with 1.9 ton/ha yield improvement with 64 kg/ha additional N treatment. The ANOVA for the improved yield could not be done, since there was no replication of the plots 12 and 13.

For the plots with no additional N, the yield showed gradual increases as the pre-applied N treatment increased (Figure 9). It is notable, however, that the subplots with more than 101 kg/ha N had no significant yield increases. The figure shows the gradual yield increase along with the N treatments but no more significant increase beyond 101 kg/ha N treatments. The statistical variation of the yield data showed higher variations in the subplots with small amount of the initial N treatments and decreasing as the N treatments increased.

Conclusions

A multi-spectral imaging sensor (MSIS) system associated with a variable rate application system was evaluated for supplemental nitrogen (N) application to corn crops based on real-time N estimates derived from the MSIS reflectance responses of crop canopies. Nitrogen uptake need of crop plants varies throughout the growing season. Nitrogen status of the plants also spatially varied over the time due to the soil, weather, and other environmental conditions. Supplemental N treatments were applied to cope with the spatial field variation based on SPAD chlorophyll meter estimates predicted from MSIS sensor response.

In one case, supplemental N treatment on the basis of real-time sensing improved the crop N status and thus could achieve the profitability of the yield production. The yield improvement was obtained over most of plots. The improvement was still valid over the plot with large amount of initial N treatments. In a view of production efficiency, the yield increase was best achieved in the plot with small amount of initial N treatments followed by the supplemental variable rate application. In another case, however, no yield improvement was observed with the MSIS-based fertilization. Yield data obtained from the plots where N applied on a later season resulted in weak impact of the supplemental N, because of a poor relationship for the N recommendations. For plots with no additional N, the yield increased gradually along with initial N treatments. It was also found that any N application more than 101 kg/ha had minimal impact on yield. Profitability of the system remains to be further studied.

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