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On-field Crop Stress Detection System Using Multi-spectral Imaging Sensor

Y. S. Kim, J. F. Reid, A. Hansen, Q. Zhang

Abstract: Nitrogen (N) management is critical for corn production. On the other hand, N leaching into the groundwater creates serious environmental problems. There is a demand for sensors that can assess the plant N deficiency throughout the growing season to allow producers to reach their production goals, while maintaining environmental quality. This paper reports on the performance of a vision-based reflectance sensor for real-time assessment of N stress level of corn crops. Data were collected representing the changes in crop reflectance in various spectral ranges over several stages of development in the growing season. The performance of this non-contact sensor was validated under various field conditions with reference measurements from a Minolta SPAD meter and stepped nitrogen treatments.

Keywords: Precision agriculture, Nitrogen stress, Spectral analysis, Real-time sensing, Ambient illumination

Introduction

In conventional agricultural practices, farmers managed their land under the assumption that each field is homogeneous. But agricultural fields are variable and require different or varying methods of crop management on specific locations in the field (Reid, 2000). The rapid development of computing, sensing, and information technologies has introduced new concepts on methods and techniques for the management and control of agricultural systems widely known as precision agriculture. High yields with low environmental impact only can be achieved with time and site specific nitrogen fertilization (Auernhammer et al., 1999). The goal of precision agriculture is not only to maximize benefit to farmers but also to enriching the naturemaintain environmental quality, leading to an economic and ecological revolution of agriculture.

Precision agriculture is a concurrent system utilizing many technologies such as Global Positioning System (GPS), Geographic Information System (GIS), vision systems, information technology, and networking. GPS is used as a basic unit of site-specific mapping. GIS serves as a part of the decision support system. Vision systems have been widely used for ground and remote sensing during growing season. Information technology provides efficient data processing and management to establish on-farm database systems. Controller Area Network (CAN) bus is also important for providing efficient, integrated on-vehicle data communication (Ekiz *et al.*, 1996). CAN bus application of distributed control to closed environments in agriculture was addressed by Alves-Serodio *et al.* (1998). The benefit of precision agriculture will be achieved by the seamless integration of all these subsystems.

Nitrogen (N) is an essential nutrient required for plant growth. Nitrogen management is critical for corn productionmidwest. On the other hand, N leaching into the groundwater creates serious environmental problems and has been linked to hypoxia problems. (Ref?). Walker *et al.* (1997) have reported that 39-89 kg/ha of excess N was treated applied during 1993-95 in East Central Illinois. The US Environmental Protection Agency (1998) pointed out that nutrients were one of the leading causes for contaminating the waterways. Nitrogen levels in many regions are higher than the drinking water standard. Thus, there is a demand for sensors that can monitor crop N requirements throughout the growing season to allow producers to reach their production goals, while maintaining environmental quality.

N is a major component of the chlorophyll molecule (Tracy *et al.* 1992). Chlorophyll is the primary absorber of light energy needed for photosynthesis (Lee *et al.*, 1999). The Minolta SPAD chlorophyll meter (SPAD 502 Chlorophyll meter, Minolta Co, Japan) has been widely used to measure crop chlorophyll concentration by many researchers (Schepers *et al.*, 1992, Peterson *et al.*, 1993, Blackmer and Schepers, 1994, Smeal and Zhang, 1994, Piekielek *et al.*, 1995, Irfan Ahmad *et al.*, 1999). They showed the feasibility of using a SPAD meter for assessing nitrogen content. Peterson *et al.* (1993) reported that before V6 stage and after silking stage, the N stress of the corn crop is not detectable.

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Vision-based reflectance sensors was have been widely used to assess plant N contents. Various studies were performed to predict N stress levels for corn (Blackmer and Schepers, 1994, Bausch *et al.*, 1998, Lee *et al.*, 1999), wheat (Filella *et al.*, 1995, Stone *et al.*, 1996), patatopotato (Borhan and Panigrahi, 1999), sweet pepper (Thomas and Oerther, 1972), bean (Thai *et al.*, 1998), cotton (Tracy *et al.*, 1992, Sui, 1999, Wilkerson *et al.*, 1999), fuffelglass (Everitt *et al.*, 1985), and poinsettia plants (Meyer *et al.*, 1991). They showed great potential for multi-spectral analysis to estimate N content of the crops. They also found that the spectral reflectance was inversely correlated to the N content of the crop canopies. Their These studies were performed based on off-field studies. Hendrickson and Han (2000), Moran *et al.* (1997) and Gopalapillai and Tian (1999) showed the potential of aerial remote sensing to detect N stress using spectral images taken from satellite and aircraft, but a major limitation that remained was the spatial resolution. To be effective for N management in precision agriculture, there is a need for a real-time sensing system that can detect plant N stresses at a high resolution while minimizing the effects of external influences. The University of Illinois in cooperation with CNH Global NV has been exploring the potential of such a sensor since 1996.

The objective of the research described in this paper was to evaluate the performance of a multi-spectral imaging sensor (MSIS) for real-time assessment of on-field N stress level of corn crops. Data were collected representing the changes in crop reflectance in various spectral ranges over several stages of crop development during the growing season. Comparisons of the performance of this non-contact sensor under various field conditions were made and validated against reference measurements made with a Minolta SPAD meter and the stepped N treatments and spectrophotometer measurements.

Materials and Methods

The MSIS system consists of an imaging sensor, an ambient illumination sensor, a differential GPS for position measurement, a portable computer, and a research sprayer platform (fig. 1). The imaging sensor was a custom developed 3-CCD multi-spectral camera(Cohu Inc., San Diego, CA), which contained three separate optical paths and video processors-detectors. Special optical filters were installed over the sensors providing three video channels of green (G), red (R), and near infra-redinfrared (NIR). These three channels of G, R, and NIR have center wavelengths of 550 nm, 650 nm, and 800 nm and bandwidth of approximately 100 nm for each channel. A special lens arrangement provides for optical alignment of three images into one as viewed on monitor RGB input. The camera is mounted inside a modified 31/2 inch barrel. The A serial interface board provideds external control of gain and shutter speed for each three independent video channel. with communication of half duplex RS232. Images were captured by an image sensor with a resolution of 640H 480V (?)at 8-bit/pixels. for each R, G, NIR channel.

A frame grabber (FlashBus MV, Integral Technologies, Inc., Indianapolis, IN) has 640H 480V pixels with RS-232 communication port) was used to acquire images through a. Hhigh speed PCI interface supportings 24-bit color video with up to 16.8 million colors.

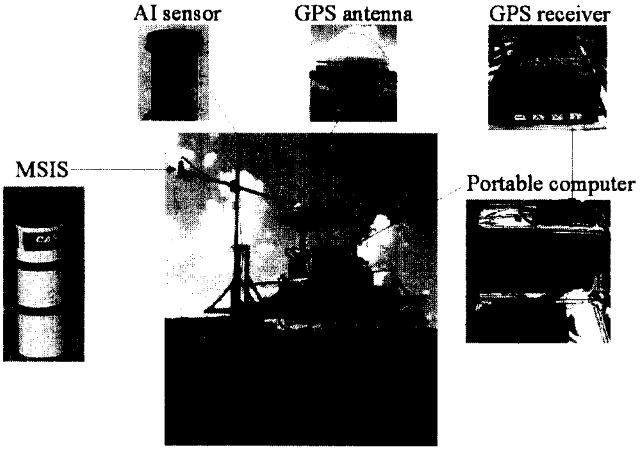

Fig. 1 Components of the MSIS system.

Ambient illumination (AI) was collected measured by using a Skye radiometer (SKR1850A 4-channel, Skye Instruments Ltd., Powys, UK). The AI sensor had four channels of G at (550 nm with 40 nm bandwidth), R (650 nm with 40 nm bandwidth), NIR (800 nm with 40 nm bandwidth), and a broadband illumination at (650 nm with 500 nm bandwidth). Differential GPS (Case IH AFS Universal Receiver, CNH Global N.V., Racine, WI) was used for scite-specific field mapping. A portable Dolch computer (PAC 586, Dolch Computer Systems, Inc., Fremont, CA) mounted on the sprayer was used to perform data collection and processing. Image analysis was implemented with Image-Pro Plus software (Media Cybernetics, L.P., ver. 3.01). Sprayer control was implemented through a microprocessor system custom-developed to provide independent nozzle control at 4 application rates. The sprayer was linked to the computer through serial communication. SPAD meter measurements waswere used to provide a chlorophyll index of the corn canopies.

Multi-Spectral Imaging Sensor (MSIS) project was established by the partnership of Agricultural Engineering in University of Illinois at Urbana-Champaign and Case Cooperation on early 1997.

The purpose of the project was to develop a vision-based spectral sensor to detect N stress and treat N with real-time feedback from the sensor. The stepwise progress has been achieved and reported regularly. Hardware construction has been regularly upgraded in parallel with software development.

Fig. 2 illustrates a conceptual layout of the entire system. A crop image from the MSIS was captured by a FlashBus frame grabber. The AI sensor was connected to an I/O card and measured the amount of ambient illumination. The variation of AI intensity dramatically affected the image quality. To compensate for the AI variation, gain and exposure were dynamically adjusted by a fuzzy control algorithm to obtain uniform images with an average gray-level value of around 128 for all three R, G, and NIR channels. New values for MSIS gain and exposure were updated duty cyclethrough a serial RS-232 connection. Once the image was convergedacquired, image it was segmented to remove non-vegetation components and processed based on histogram distribution. Differential GPS records and provides geometric informationposition is automatically recorded with each image. The vegetation component of the image was used to assess the reflectance of crop rows or other areas of interest. Finally, a decision was made based on information given by the system and output was sent to the sprayer controller.

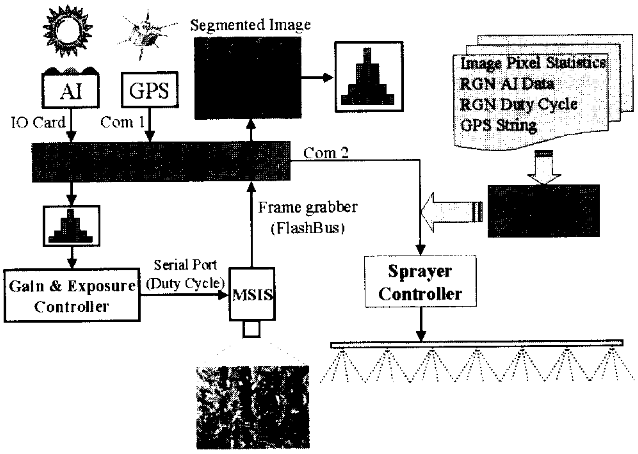

Fig. 2 A conceptual layout of real-time MSIS system.

The basic response for the MSIS was developed based on solar energy transformation and determined as a function of average gray-level value (GL_{ave}), ambient illumination (AI), exposure (E), and gain (G) as following:

$$\text{MSIS response} = f(Gl_{ave}, AI, E, G). \tag{1}$$

Other indices to identify N stress level that were used in this study were normalized response, normalized difference vegetative index (NDVI) (Steven and Millar, 1997), and N sufficiency index (NSI) (Bausch *et al.*, 1997).

1. MSIS calibration

Three MSIS system has been gradually upgraded from a gain-fixed version (Dycam, Chatsworch, CA) and an analog version of Cohu MSIS system to a current serial version during past three years. The serial version of Cohu MSIS system was developed to incorporate sensor gain and exposure control based on user-selectable regions of interest. Thesensor calibration was used to determine the relationship between MSIS response and absolute reflectance panels. Three MSIS units paired with AI sensors were calibrated using the USDA-ARS goniometer at the Maricopa Agricultural Center (MAC) in Arizona (fig. 3). The basic procedure involved mounting an MSIS sensor, an AI sensor, and a known absolute reflectance panel (White Reflectance Standards, Munsell product, GretagMacbeth LLC, New Windsor, NY) on the goniometer. The goniometer was adjusted to orient all three components normal to the direction of the incident solar ray. The responses were recorded for the full range of the MSIS sensor gains. The experiment was implemented at around solar noon to reduce effects of the solar atmosphere and the surrounding environment.

Fig. 3 Sensor calibration using a goniometer.

2. Evaluation of MSIS response to crop stress

Experiments were conducted at MAC in Arizona. The MSIS system and associated software were used to evaluate the performance of the sensor under field conditions. A corn crop was planted on two plots in early and late February. Each plot had 16 rows spaced 76.2 cm apart and of length 105m. Plots were established by applying variable levels of N to create differences in crop stress. In addition to N variations, at the time the measurements were made the plants appeared to be water stressed, although this was not documented. A total of eight nitrogen treatments were applied on individual plots of 6.1 m length throughout the growing season(Table 1). Each nitrogen treatment was replicated four times and was ordered from low to high N then high to low N from the beginning to end of the field. The plots were maintained by University of Arizona personnel as necessary with irrigation, fertilizer, weed control, and insect control. Data collection took place just prior to tasseling stage on May 16-18, 2000.

Table 1 Nitrogen treatment [lbs/acre] for corn.

N rate (Total)	Pre-plant	V8 stage	V16 stage
0	0	0	0
25	12	8	5
50	25	15	10
100	50	30	20
150	75	45	30
200	100	60	40
300	150	90	60
500	250	150	100

Results and Discussion

1. MSIS calibration

Three MSIS units were calibrated at MAC consecutively around noon on May 18, 2000. A 20% reflectance panel was used as the known absolute reflectance. Calibration coefficients were obtained for the R, G, and NIR channels of each unit.

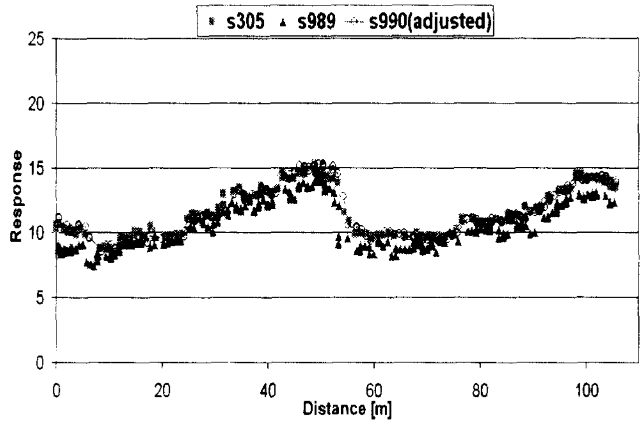

Fig. 4 Reflectance responses in G channel of three MSIS.

To validate the sensor coefficients obtained through calibration, the MSIS responses of the three units (MSIS305, MSIS989, and MSIS990) were compared. The MSIS units were subsequently used to measure the reflectance on corn in sequence. The experiment consisted of mounting the MSIS on the sprayer plat

Subsequent runs were made with each of the MSIS units at the same row. It was found that one unit (MSIS990) deviated slightly from the others. Through analysis it was discovered that the different sensitivity of its AI sensor was the main cause for this deviation. After adjusting the AI values for that unit to a uniform scale, all the MSIS sensors displayed comparable performance when used to measure stresses on crop in the field (fig. 4).

2. MSIS response to crop stress

The MSIS system was used to detect the crop response relative to N application treatment and SPAD measurements. The crop stresses were clearly evident according to the stepped treatment of N. The SPAD readings ranged from 19-24 for severely stressed plants to 45-53 for non-stressed plants.

Two methods were used to evaluate the sensor response. The first was to make comparisons between individual images and SPAD measurements at specific locations in the field. Fig. 5 shows that the normalized MSIS response and SPAD are inversely related. Strong correlation was achieved between the normalized MSIS responses and SPAD measurements with -0.8816 and -0.9314 for R and G channels, respectively.

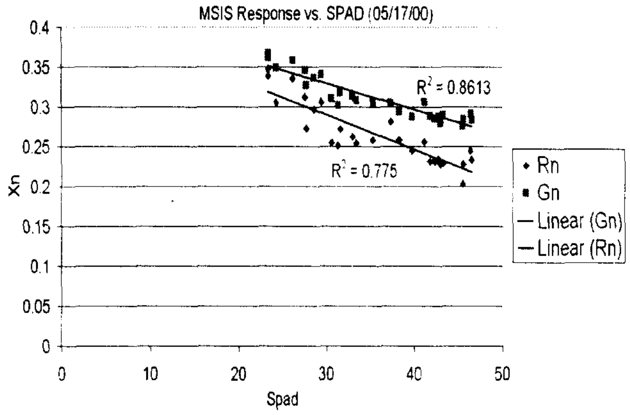

Fig. 5 Comparison between the normalized MSIS response and SPAD measurement of corn.

The second evaluation method compared the real-time response of the three MSIS units by recording data on subsequent passes by running 0.5 m/sec vehicle speed through the field to map the response of an individual row. SPAD measurements were made at specific locations along the row. The response of each MSIS unit to the same field locations was compared using this method. MSIS responses were computed in real-time with distance along the row for each unit.

The spatial distribution of MSIS green responses (fig. 6) was compared with the N treatments. The response trends were identical among the units and followed closely the field distribution (fig. 7) of stressed crops as well as variation of early N treatments. The slight deviation of one unit (MSIS990) was removed by normalizing the response in which AI value terms were eliminated out by dividing the G channel response by the NIR channel response.

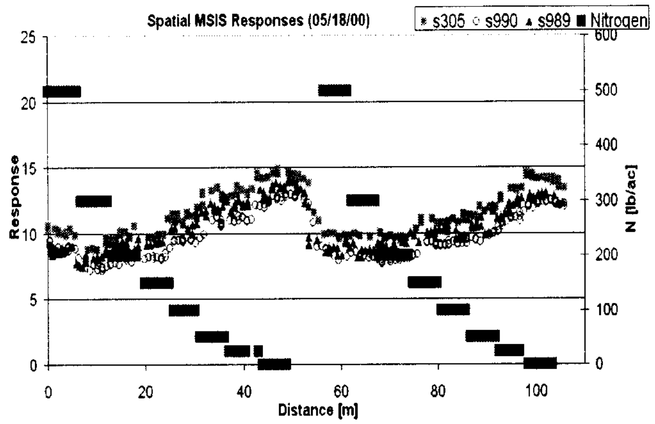

Fig. 6 Raw response of three MSIS units in green channel along a fixed corn crop row.

Fig. 7 Characteristics of corn field with early applied stepwise N treatment.

Spatial comparison between the normalized MSIS green response recorded real-time and individual SPAD measurements are illustrated in fig. 8. Close correspondence was obtained between the units. The normalized MSIS response from all three units showed a stable distribution, while the SPAD measurements had more variation. Since the SPAD meter measured only a small area of 2 mm × 3 mm (Spectrum Technologies, Inc., 2000) on the plant leaf, the measurements at each location were insufficient to represent the crop field characteristics over the wider area captured by the MSIS.

N deficiency was estimated by using NSI which is calculated from normalized NDVI. The spatial distribution of real-time N deficiency using MSIS 305 unit is plotted in fig. 9. NSI provides an N deficiency level relative to unstressed healthy crop. The fig. 9 shows the deficiency trend of NSI follows that of SPAD measurements. The index for non-stressed crops is 1 and corresponds to a SPAD value of 46, while most stressed crops were matched to a SPAD measurement of 24 and had NSI values just below 0.9.

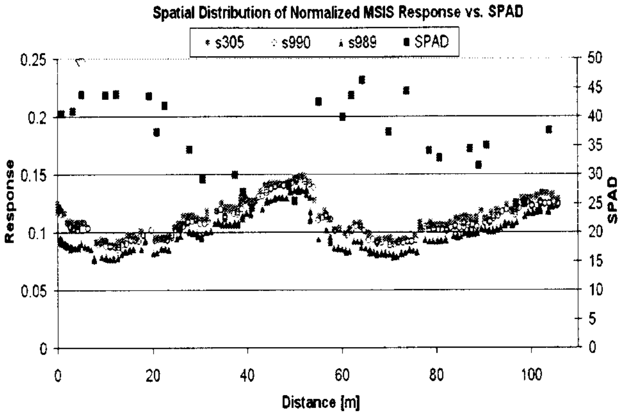

Fig. 8 Comparison of real-time spatial response between normalized MSIS green response from three MSIS units and SPAD measurements along the same crop row.

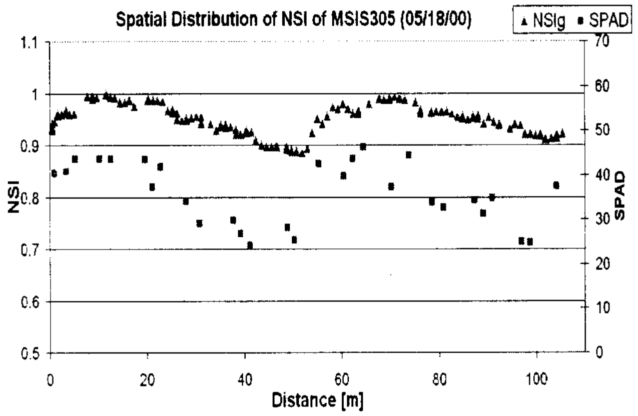

Fig. 9 Spatial distribution of real-time N deficiency along a single crop row.

Conclusions

This paper reports on the evaluation of a custom-developed imaging system for detecting crop reflectance as a tool for nitrogen management. The MSIS provided a non-contact method for monitoring crop stress. Image processing provides the ability to remove the effects of non-vegetation components from images that have been difficult to account for in radiometric studies of crop responses. The MSIS units were calibrated and tested. Comparable performance among the units was achieved by the calibration.

The performance of the MSIS system in detecting N stress was evaluated with newly developed software on the experimental plot prepared with stepped N treatments. The responses were collected along with SPAD mapping on specific locations of the field. Strong correlation was achieved between normalized MSIS responses and SPAD measurements with correlation coefficients −0.8816 and −0.9314 for R and

G channels, respectively. Real-time MSIS responses were recorded and compared among three MSIS units. Close correspondence was obtained between units. The response trends were almost identical with the field distribution of stressed crop plants as well as variation of early N treatment. The SPAD measurements on small area of leaf canopy at each location were not sufficient to represent the crop field characteristics over the wider area captured by the MSIS. Real-time N deficiency was estimated by using NSI and mapped relative to unstressed healthy plants. Continuing work includes evaluation of the MSIS as a management tool for precision agriculture.

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