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Evaluation of two crop canopy sensors for nitrogen variability determination in irrigated maize

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Abstract Advances in precision agriculture technology have led to the development of ground-based active remote sensors that can determine normalized difference vegetation index (NDVI). Studies have shown that NDVI is highly related to leaf nitrogen (N) content in maize (*Zea mays* L.). Remotely sensed NDVI can provide valuable information regarding in-field N variability and significant relationships between sensor NDVI and maize grain yield have been reported. While numerous studies have been conducted using active sensors, none have focused on the comparative effectiveness of these sensors in maize under semi-arid irrigated field conditions. Therefore, the objectives of this study were (1) to determine the performance of two active remote sensors by determining each sensor's NDVI relationship with maize N status and grain yield as driven by different N rates in a semi-arid irrigated environment and, (2) to determine if inclusion of ancillary soil or plant data (soil NO_3 concentration, leaf N concentration, SPAD chlorophyll and plant height) would affect these relationships. Results indicated that NDVI readings from both sensors had high r^2 values with applied N rate and grain yield at the V12 and V14 maize growth stages. However, no single or multiple regression using soil or plant variables substantially increased the r^2 over using NDVI alone. Overall, both sensors performed well in the determination of N variability in irrigated maize at the V12 and V14 growth stages and either sensor could be an important tool to aid precision N management.

Keywords Crop canopy sensors · Remote sensing · NDVI

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Introduction

Recent advances in precision agriculture technology have led to the development of ground-based active remote sensors (or crop canopy sensors) that calculate NDVI readings. Previously this index was determined using passive sensors via airborne or satellite imagery which had several limitations including expense and weather related issues such as cloud cover that could greatly limit the effectiveness of these sensing techniques. Active sensors have their own source of light energy and allow for the determination of NDVI at specific times and locations throughout the growing season without the need for ambient illumination or flight concerns. Crop canopy sensors are relatively small in size and contain an integrated light source. They operate by directing visible light (VIS) (400–700 nm) as well as near infrared (NIR) (700–1300 nm) light at the plant canopy of interest. The amount of VIS and NIR light that is reflected by the plant canopy is measured and an NDVI value is calculated using the following equation:

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{VIS})/(\mathrm{NIR} + \mathrm{VIS}) \tag{1}$$

where *NIR* near infrared and *VIS* visible light wavelength

The visible light reflectance is primarily dependant on the chlorophyll contained in the palisade layer of the leaf and the NIR reflectance depends on the structure of the mesophyll cells and the cavities between these cells (Campbell 2002). A strong linear relationship exists between leaf chlorophyll concentration and leaf nitrogen (N) concentration (Ercoli et al. 1993). Therefore, greater leaf area and green plant biomass levels result in higher reflectance and higher subsequent NDVI values. Because these variables are directly related to the N content of the plant, higher NDVI values indicate higher plant N content. These properties allow NDVI to be a valuable tool in determining the relative plant N status by comparing the NDVI of plants with sufficient N to the NDVI of plants with an N deficiency.

Studies with maize have shown that leaf reflectance (near 550 nm wavelength) has a good relationship with leaf N content (Alchanatis et al. 2005; Osborne et al. 2002). Other studies have been conducted verifying that remotely sensed imagery can provide valuable information about in-field N variability in maize (Sripada et al. 2005; Chang et al. 2003). High coefficients of determination (r^2) between NDVI and maize grain yield have also been found (Chang et al. 2003; Osborne et al. 2002).

Studies specific to crop canopy sensors have shown that NDVI readings adequately quantify maize variability (Raun et al. 2005) and relate well with many variables that affect maize yield. Martin et al. (2007) found that NDVI increased with maize growth stage during the crop life cycle and a linear relationship with grain yield was best at the V7–V9 maize growth stages (Ritchie et al. 1986). This study also found that NDVI increased until the V10 growth stage when a plateau was reached and NDVI began to decrease after the VT growth stage. Freeman et al. (2007) reported a good relationship of NDVI × plant height of maize at V8–V10 growth stage with plant by plant forage yield on an area basis and suggested that this index may be used to refine mid-season fertilizer N rates based on expected N removal at or before V10. Substantial r^2 values have also been shown between NDVI and maize forage and grain yields when NDVI readings are collected between the growth stage development window of V5–V9 (Thomason et al. 2007). Similar results were found by Teal et al. (2006) with NDVI and grain yield relations between the V7–V9 growth stages. Inman et al. (2007) found that an active sensor-produced NDVI-ratio calculated between the reflectance of the “area of interest” and from “an N-rich, or non-N limiting portion" of the same field had a significant relationship with observed maize grain yield. The authors suggested that this NDVI-ratio has the potential to estimate maize grain yield; however, improvements need to be made.

Review of the literature indicated that numerous studies have been conducted with respect to remote sensing and its applications in crop production. However, there are no studies that have focused on using a pair of commercially available crop canopy sensors to study their comparative effectiveness under field conditions in a semi-arid irrigated environment.

This study is a part of a large active sensing project, the overall goal of which is to develop an N recommendation algorithm based on sensor collected NDVI values. However, the first course of action was to establish which commercial sensor would perform best under a semi-arid irrigated continuous maize production environment. It was also necessary to identify the optimum growth stage at which each sensor performed best and if ancillary variables that are related to maize growth could be used in conjunction with NDVI readings to increase the effectiveness of each sensor. The ancillary variables included soil NO_3 concentration (0–0.2 m depth), flag leaf total N concentration, leaf chlorophyll content and plant height. Each variable is known to be affected by overall maize growth. Therefore, it was hypothesized that the relationship between NDVI and grain yield could be improved by increasing the number of biophysical parameters measured, thereby increasing measurement of crop variability.

The objectives of the study were: (1) To determine the effectiveness of two commercially available active sensors across several maize growth stages and N application rates under semi-arid irrigated environmental conditions. (2) To determine if ancillary soil and crop variables known to affect maize growth and yield can be used in conjunction with NDVI to strengthen sensor measurements of crop variability.

Materials and methods

Study sites

This study was conducted on two sites in 1 year (2 site years) at the Agricultural Research Development and Education Center (ARDEC) located near Fort Collins, Colorado, USA (latitude 40°40′ 38.24″ N, longitude 104° 59′ 44.76″ W) during the summer of 2006. Soils at the two sites were classified as a fine-loamy, mixed, superactive, mesic, Aridic Haplustalf (Soil Survey Staff 1980) and were under furrow irrigated continuous maize cropping system.

Nitrogen application and plot design

The nitrogen rate variables were imposed using 32-0-0 urea–ammonium–nitrate (UAN) applied at emergence (no pre-plant N was applied) using a 4-row side-dress applicator with variable rate capabilities. This applicator applied liquid N 50–100 mm below the soil surface and to the side of the maize plant. The N was applied immediately before a scheduled irrigation. Four N rates were applied; 0, 50, 100 and 175 kg N ha^{-1}. Each N rate was replicated four times at each site year in a complete randomized block (CRB) design. Each plot was 4 maize rows in width (0.76 m row spacing) and 15 m in length. Site years 1 and 2 had not received applied N for 2 years prior to this study.

Sensors

Two active sensors were tested and compared across two site years. The active sensors tested included the red GreenSeeker™ Model 505 hand held optical sensor (NTech Industries Inc., Ukiah, CA, USA). The principles and physics behind the operation of this sensor are described in detail in Inman et al. (2005). The GreenSeeker™ active sensor operates by directing VIS red light (660 nm) as well as NIR light (770 nm) at the plant canopy. Therefore, the GreenSeeker™ sensor will be referred to as the "red sensor". The amount of visible and NIR light that is reflected by the plant canopy is measured and a normalized difference vegetation index (NDVI) value is calculated. The NDVI equation is shown above. The NDVI value is a broadband index that is highly related to leaf area index and green biomass (Penuelas et al. 1994), and therefore, photosynthetic efficiency (Aparicio et al. 2002). The GreenSeeker™ generates a red light (660 nm) in the visible spectrum and therefore, the NDVI value calculated by the GreenSeeker™ will be referred to as "Red NDVI".

The second sensor was the Holland Scientific Crop Circle™ ACS-210 Plant Canopy Reflectance Sensor (Holland Scientific, Lincoln, NE, USA). The Crop Circle™ sensor is also active and operates under the same principles as that of the GreenSeeker™ sensor; however, the Crop Circle™ sensor generates light with a wavelength of 590 nm in the VIS band and 880 nm in the NIR band. The visible light produced by this sensor (590 nm) is called "yellow" by the manufacturer (Holland Scientific 2005) but has also been referred to as "amber". Therefore, this sensor will be referred to as the "amber sensor" and the index calculated will be referred to as "Amber NDVI".

While NDVI was the index used to compare the crop canopy sensors in this study, other indices using NIR and VIS reflectance can be calculated using these sensors. These include, but are not limited to: simple ratio (NIR/VIS), inverse simple ratio (VIS/NIR), and soil adjusted vegetation index $(NIR - Red/NIR + Red + L) \times (1 + L)$ (where: $L =$ soil brightness factor). The purpose of this study was to determine the effectiveness of each sensor, not any one vegetation index. Therefore, NDVI was used as the basis of comparison for each sensor as NDVI is a very common and established vegetation index.

Sensor readings were collected across four N application rates at the V8, V10, V12 and V14 maize growth stages for site years 1 and 2. Active sensors were mounted on a telescopic boom allowing readings to be collected at all maize growth stages. The red sensor was held 1 m above the maize canopy. This is in the middle of the range (0.8–1.2 m) suggested by the manufacturer's instruction manual (NTech Industries, Inc., 2005). The amber sensor was held 0.7 m above the maize canopy as readings were collected. This is in the middle of the manufacturers range (0.5–0.9 m) for this sensor (Holland Scientific 2005). The red sensor was connected to a Compaq Ipaq™ H3900 Pocket PC (Compaq Computer Corp., Houston, TX, USA) to record NDVI values. The amber sensor was connected to a Holland Scientific GeoSCOUT GLS-400 (Holland Scientific, Lincoln, NE, USA) data logger to record NDVI values.

Supplemental sampling and analysis

Supplemental plant and soil sampling was conducted at maize growth stages V8, V10, V12 and V14. This sampling was done at the same time that sensor NDVI readings were collected. The sampling included the most mature leaf for total N content, plant height, soil NO_3–N content and SPAD chlorophyll readings.

Maize leaves were collected from 10 random plants across all N application rates. Maize leaf total N content was determined by 2% acetic acid digestion and inductively coupled plasma (ICP) spectrometry by AgSource Harris Labs in Lincoln, NE, USA.

Maize plant height was recorded using a meter-stick measuring from the furrow bed to the highest point of the maize plant. Five random measurements were collected across each N application rate and were averaged to attain one plant height number per plot.

Soil sampling was conducted in each N application plot. Samples were collected from ten random locations within each plot and were taken from a depth of 0–0.2 m. The ten samples from each plot were then combined and mixed to yield one composite soil sample per plot. Soil samples were then analyzed for NO_3–N content with the colorimetric method using KCL extraction and cadmium reduction (Mulvaney 1996) by AgSource Harris Labs in Lincoln, NE, USA.

The SPAD chlorophyll meter readings were collected within each N application rate plot. Readings were collected from five random most mature leaves in each plot at the V8, V10, V12, and V14 growth stages. The readings were averaged to yield one SPAD reading per N application rate plot. SPAD readings were collected using a Minolta SPAD-502 chlorophyll meter (Konica Minolta Sensing Inc., Osaka, Japan).

Maize grain yield

Maize grain yield was determined by harvesting with a two-row Massey Ferguson plot combine (only the center two rows of each plot were harvested) equipped with a Harvest Master HM-401 CCU yield monitor (Juniper Systems Inc., Logan, Utah, USA) which recorded grain weight over distance traveled. Grain sub-samples were collected during the harvesting operation and moisture and test weight determined using a Dickey-john® GAC model 2100 grain analysis computer (Dickey-john Corp., Auburn, Illinois, USA). The grain weight was adjusted to 15.5% moisture and scaled to a Mg ha^{-1} yield basis.

Data analysis

All statistical analysis was performed using the Statistical Analysis System (SAS) (SAS Institute 2006). All regressions were performed using the REG procedure in SAS and the option STEPWISE in the REG procedure was used for all stepwise regression analysis. Segmented regression was conducted using the Proc NLIN procedure in SAS for the instances where N response reached a plateau. Procedure ANOVA was used for all analyses of variance and least significant difference calculations. Proc MEANS was used for all means calculations.

Results and discussion

Maize grain yield

Grain yield was significantly increased by applied N fertilizer in both site years relative to the unfertilized check (Figs. 1, 2). Yields were higher in site-year 1 relative to site-year 2, and the 175 and 100 kg ha^{-1} N application rates produced equal yields suggesting that the 100 kg ha^{-1} rate supplied sufficient N for maximum yield.

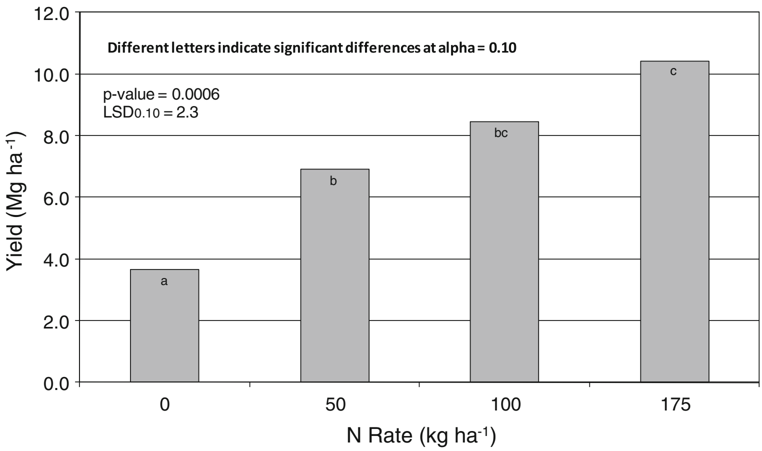

Fig. 1 Maize grain yield across 4 applied nitrogen rates at site year 1

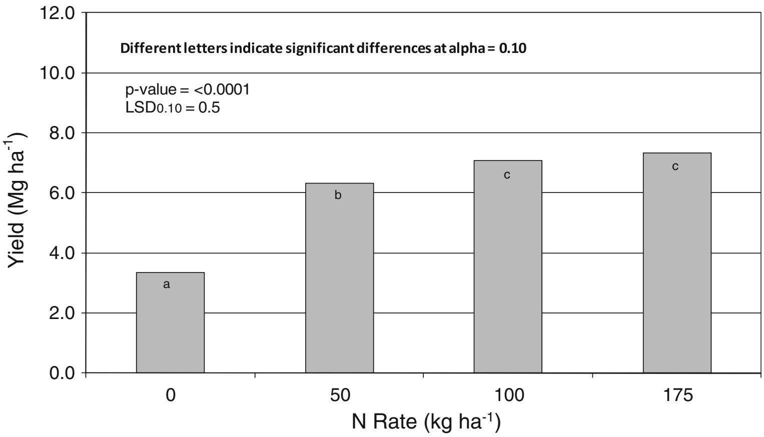

Fig. 2 Maize grain yield across 4 applied nitrogen rates at site year 2

The yield differences due to N application indicate that there are sufficient differences in maize growth in both site-years 1 and 2 to test the active sensors over a range of plant N responses. The treatments that yielded highest should have greater NDVI values and vice versa as greater plant biomass and N content are usually directly related to applied N and grain yield. If a sensor were performing properly, NDVI readings should increase across the 0, 50 and 100 kg ha^{-1} N application rates and then reach a plateau across the 100 and 175 kg ha^{-1} N rates. With no significant increase in grain yield above the 100 kg ha^{-1} N rate, a plateau in NDVI readings above 100 kg N ha^{-1} should be expected. Consequently, a segmented regression (linear-plateau model) was used to describe NDVI readings. This model also has been used when NDVI plateaus with maize LAI, maize forage yield (Thomason et al. 2007) and when maize grain yield plateaus with applied N rate (Dellinger et al. 2008; Varvel et al. 2007). By using the linear-plateau model, a more accurate fit was achieved. This analysis was the appropriate regression to the data as compared to simple linear regression.

Sensor comparison

The NDVI readings across N application rates and V8, V10, V12 and V14 maize growth stages are shown for both the amber (Fig. 3) and red (Fig. 4) sensors for site-year 1 and for the amber (Fig. 5) and red (Fig. 6) sensors for site year 2. The amber and red sensor results were the function of a 2-way applied N rate × maize growth stage interaction for both site-year 1 and site-year 2. However, it was determined that coefficients of determination of NDVI with applied N rate would be the best indicator of sensor performance, and thus comparisons were based on this analysis. The amber and red sensors responded similarly across all N treatments and growth stages. The primary difference between sensors is the range in which the NDVI readings were recorded. The amber sensor's NDVI range was approximately 0.270–0.700, whereas the red sensor had a wider range of NDVI readings

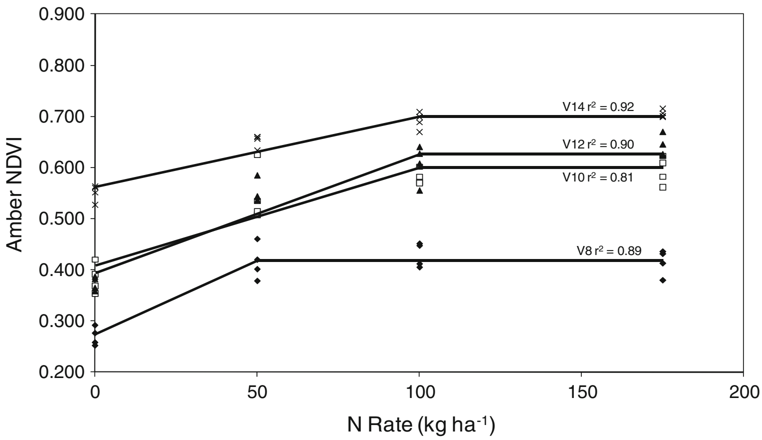

Fig. 3 Amber NDVI linear relationship with 4 applied nitrogen rates across 4 maize growth stages for site year 1

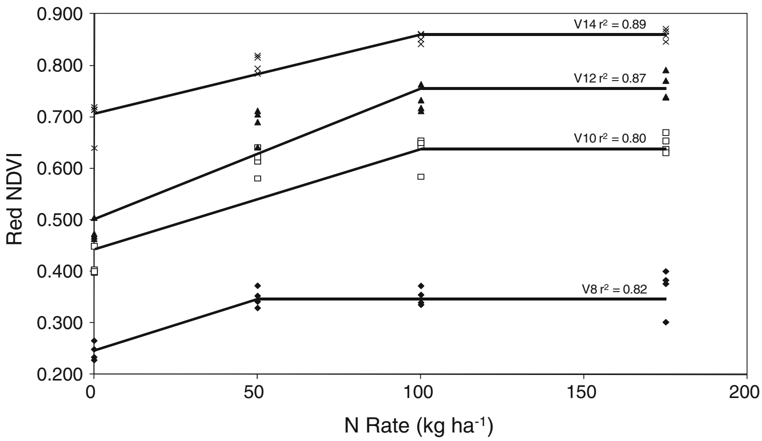

Fig. 4 Red NDVI linear relationship with 4 applied nitrogen rates across 4 maize growth stages for site year 1

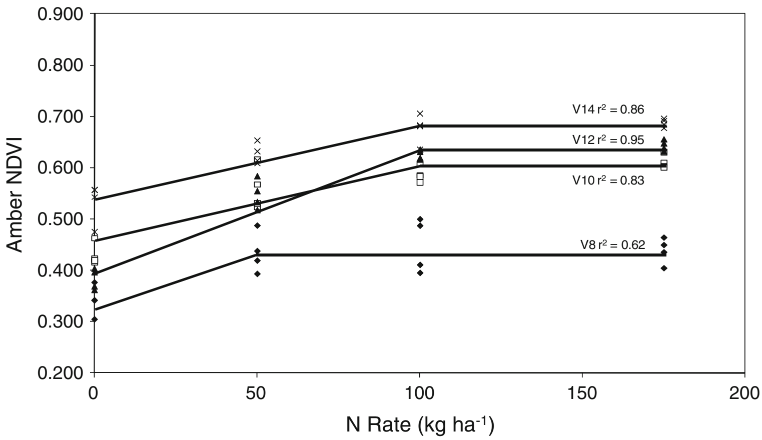

Fig. 5 Amber NDVI linear relationship with 4 applied nitrogen rates across 4 maize growth stages for site year 2

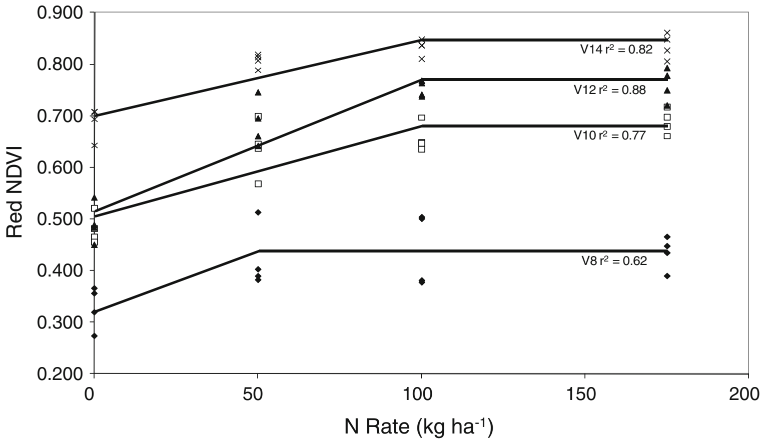

Fig. 6 Red NDVI linear relationship with 4 applied nitrogen rates across 4 maize growth stages for site year 2

from approximately 0.250–0.860. Differences in amber and red sensor NDVI range can also be seen in the algorithms developed by Kitchen (2006). This difference is a function of the different wavelengths used by each sensor and did not affect the NDVI by applied N rate r^2 values. It does suggest, however, that the red sensor could reach saturation earlier in the growing season than the amber unit, potentially limiting the use of the red sensor at later growth stages when the plant biomass is larger.

For both site years at the V8 maize growth stage, an increase in NDVI was observed between the 0 and 50 kg ha^{-1} N treatments for both sensors. At this point, the NDVI readings reached a plateau across the 50, 100 and 175 kg ha^{-1} rates; NDVI levels were not significantly different for each sensor. The plateau observed with each sensor occurred because biomass differences due to N fertilization had not developed at the V8 growth stage except when compared to the check treatment. High r^2 values between NDVI and N rate were observed for both sensors at site year 1 with the amber sensor having an r^2 of 0.89 and the red sensor an r^2 of 0.82. The r^2 values at V8 in site year 2 were lower than site year 1 with r^2 values of 0.62 for both sensors. At the V10, V12 and V14 maize growth stages, each sensor showed increasing NDVI readings across the 0, 50 and 100 kg ha^{-1} applied N rates and then a plateau occurred between the 100 and 175 kg ha^{-1} N treatments. The NDVI values also increased across maize growth stage. This also has been reported in studies by Martin et al. (2007) and Raun et al. (2005) who showed increasing NDVI with maize growth stage until tassel (VT) when NDVI then decreased due to the light scattering off of the corn tassel. Freeman et al. (2007) and Teal et al. (2006) also showed that NDVI increased with forage biomass showing a direct link with increased biomass and reflectance, which also suggests that NDVI would increase with growth stage.

High r^2 values were found between NDVI and N rate at each maize growth stage with each sensor output generally increasing as growth stage increased. At the V14 growth stage, the sensors showed very high correlations with N rate with r^2 values of 0.92 (amber) and 0.89 (red) at site year 1 and r^2 values of 0.86 (amber) and 0.82 (red) at site year 2. Similar r^2 values were observed at the V12 maize growth stage with r^2 values of 0.90 and 0.87 for the amber and red sensors, respectively, at site year 1 and r^2 values of 0.95 (amber) and 0.88 (red) at site year 2. These results suggest that the sensors perform best at the V12–V14 stages. Studies conducted in other regions of the USA have shown that earlier growth stages (V6–V10) are the optimum times to take NDVI readings (Kitchen 2006; Raun et al. 2005), based on timing related to maize N variability expression. Maize N variability expression appears to occur later in the growing season under the semi-arid irrigated environment in Colorado than in the mid-western areas of the USA. This could be related to climatic differences such as growing degree-day and precipitation differences, inherent soil variability or management practices such as irrigation management, planting dates or maize variety differences that are region specific. Studies conducted in Nebraska, USA (Solari et al. 2008; Varvel et al. 2007) were based on data collected between growth stage V11 and V15 suggesting that variability expression is later in the growing season in Nebraska as well.

Both sensors had similar r^2 values across each growth stage which leads to the conclusion that both sensors operate well under field conditions. However, the potential limitation of saturation of the red sensor must be considered as growth stage increases above V14.

Overall, the relationships of NDVI with N rate were high for both site-years at maize growth stages V12 and V14, and our results suggest that there was no significant difference in performance between the amber and red sensors when determining N variability. This supports the results of individual studies of the amber (Solari et al. 2008) and red (Raun et al. 2005) sensors. The r^2 values observed suggest that V12–V14 should be the growth stage range in which management decisions based on NDVI readings should be made under semi-arid irrigated conditions in Colorado.

NDVI and ancillary variable relationships with grain yield

Crop canopy sensors are currently being used to determine in-season N status of maize; however, relating sensor calculated indices (such as NDVI) with end of season grain yield has proven largely ineffective. It was thought that by adding measurable ancillary crop or soil variables known to affect grain yield (total plant N, SPAD chlorophyll, plant height and soil NO_3) with NDVI, the relationship of sensor calculated NDVI with grain yield could be improved, potentially increasing the effectiveness of the sensor. To test this, NDVI was regressed across maize grain yields to determine NDVI to grain yield linear relationships and then by performing stepwise regression analysis using NDVI and all measured ancillary variables to determine if any combination of ancillary variables used in conjunction with NDVI increased the coefficient of determination over using NDVI alone. This process was repeated over the V8, V10, V12 and V14 maize growth stages to determine if certain combinations performed better at specific growth stages.

The NDVI values had high r^2 with maize grain yield at the V12 and V14 growth stages for both the amber and red sensors in both site years (Table 1) and r^2 values were higher for site-year 2 than for site-year 1. The r^2 values of NDVI with grain yield are quite high for site-year 2 at V12 and V14 (approximately 0.9). For site-year 2, in-field N differences that affect plant greenness, leaf biomass, overall N status of the plant and, ultimately, grain yield, appear to be well expressed by the plants and the active sensors were able to distinguish this variability within this growth stage range. The linear relationships for site-year 1 were lower at V12 and V14 (approximately 0.7) demonstrating the variability in grain yield relationships with NDVI, even though linear relationships with N application variability are equally high across each site.

The NDVI r^2 values with grain yield are similar to what has been reported in the literature. Teal et al. (2006) found r^2 for red NDVI linear relationships with maize yield to be 0.7–0.0.8; however, this was at the V8 maize growth stage. Inman et al. (2007) reported r^2 levels of 0.65 for red NDVI with grain yield and Shanahan et al. (2001) reported airborne green NDVI linear relationships with yield as high as 0.92 during maize mid-grain filling. Our results as well as those of past studies show that there is a wide range of variability when relating NDVI with grain yield, indicating that such relationships may be location and or hybrid specific. This variability can make it very difficult to direct N recommendations using grain yield linear relationships alone.

Our stepwise multiple regression analysis revealed that only three significant multiple regression relationships existed (Table 1). The first two occurred in site-year 2 at growth stage V10 with amber NDVI and leaf N content ($r^2 = 0.89$), and at growth stage V14 with leaf N content, and plant height variables ($r^2 = 0.95$). While these linear relationships had high r^2, they are not substantially greater than those of NDVI alone. The third significant multiple regression occurred in site-year 1 at the V12 growth stage with soil NO_3–N and total leaf N contents ($r^2 = 0.84$); however, soil NO_3 content did not have a significant linear relationship with grain yield at any growth stage at either site year. Consequently, it is believed this result is an artifact of the data.

Relationships between NDVI and grain yield were not improved by the inclusion of the ancillary variables. However, the results confirm that there are linear relationships between N rate and NDVI at the V12–V14 growth stages and that crop canopy sensors can be used to determine plant N variability in fields in a semi-arid continuous maize irrigated environment.

Conclusions

The amber and red active remote sensors evaluated in this study showed similar linear relationships with applied N application rates under field conditions. Each sensor had significant NDVI to applied N rate linear relationships ($r^2 > 0.89$), and were able to determine maize N variability across fields under irrigated conditions in Colorado. Numerically, the highest r^2 values occurred at the V14 maize growth stage for site-year 1

Table 1 Amber and red NDVI, SPAD chlorophyll content, plant height, soil N concentration and maize flag leaf N concentration individual and stepwise regression with maize grain yield for site years 1 and 2

	Site year 1 *R*-square	Site year 2 *R*-square
V8 variable correlation		
Amber NDVI	0.51	0.45
Red NDVI	0.49	0.28
SPAD	0.39	0.69
Soil N	0.31	0.22
Leaf N	0.64	0.85
Plant height	0.45	0.37
Multiple regression	–	–
V10 variable correlation		
Amber NDVI	0.59	0.79
Red NDVI	0.66	0.74
SPAD	0.59	0.79
Soil N	0.05	0.05
Leaf N	0.74	0.79
Plant height	0.62	0.77
Multiple regression	–	0.89 (amber NDVI + Leaf N)
V12 variable correlation		
Amber NDVI	0.69	0.87
Red NDVI	0.66	0.84
SPAD	0.57	0.79
Soil N	0.10	0.20
Leaf N	0.74	0.46
Plant height	0.49	0.86
Multiple regression	0.84 (Soil N + Leaf N)	–
V14 variable correlation		
Amber NDVI	0.71	0.88
Red NDVI	0.75	0.91
SPAD	0.43	0.54
Soil N	0.27	0.08
Leaf N	0.50	0.21
Plant height	0.61	0.79
Multiple regression	–	0.95 (amber NDVI + Leaf N + Ht)

and at the V12 maize growth stage for site-year 2, but the V12 and V14 NDVI linear relationships with N rate were essentially equal for both site-years. This suggests that the optimum time to take NDVI readings in Colorado may be the V12–V14 maize growth stage range; however; growth stages later than V14 were not evaluated. Multiple step-wise regression analysis revealed that the use of ancillary crop and soil variables related to crop growth did not improve sensor effectiveness over that of NDVI alone in terms of grain yield prediction.

Both the NTech GreenSeeker™ red sensor and the Holland Scientific amber Crop Circle™ sensors performed well in the determination of N variability in irrigated maize at the V12 and V14 growth stage and could be very important tools for determining in-season maize N requirements.

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