DISSERTATION

GROUND BASED ACTIVE REMOTE SENSORS FOR PRECISION NITROGEN MANAGEMENT IN IRRIGATED MAIZE PRODUCTION

Submitted by

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In partial fulfillment of the requirements

For the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Spring 2009

COLORADO STATE UNIVERSITY

April 7, 2009

We hereby recommend that the dissertation prepared under our supervision by Timothy M. Shaver entitled "Ground based active remote sensors for precision nitrogen management in irrigated maize production" be accepted as fulfilling, in part, the requirements for the degree of Doctor of Philosophy.

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ABSTRACT OF DISSERTATION

GROUND BASED ACTIVE REMOTE SENSORS FOR PRECISION NITROGEN MANAGEMENT IN IRRIGATED MAIZE PRODUCTION

One of the goals of agronomists is to enhance the efficiency of farm inputs without negatively impacting profitability or the environment. Precision farming can increase input efficiency by accurately quantifying variability within a field. Several methods have proven successful in identifying variability and the majority of methods use some form of remote sensing. Remotely sensed indices can provide valuable information about plant variability. One particular remotely sensed index, normalized difference vegetation index (NDVI), has been shown to be directly associated with maize (*Zea mays*) N content. Ground-based active remote sensors that can determine NDVI are commercially available and have been shown to accurately distinguish N variability in maize. Active sensors have also been shown to be effective in maize N recommendation algorithms. There are several active sensors available but no studies on active sensors have been conducted in Colorado and no studies have been reported that directly compare sensors to determine which performs best in determining N variability. Therefore, a study was conducted with three objectives: (1) to determine if a prototype active sensor could effectively verify previously delineated production level management zones (MZ). (2) To evaluate and compare two commercially available active sensors in determining N

variability in maize under greenhouse and field conditions. (3) Develop an in-season maize N recommendation algorithm for use in Colorado based on NDVI.

The first objective was to determine if a prototype active sensor could effectively verify previously delineated production level management zones (MZ). One way to enhance the efficiency of on farm inputs is through the adoption of production level management zones. Previous studies have demonstrated an association of NDVI with maize N content and height suggesting that NDVI could be a good indicator of MZ as maize N content and height vary by MZ due to characteristics within each zone that dictate plant growth and yield. Therefore, a proto-type active sensor (GreenSeeker™ green) was evaluated to determine if differences in plant growth across MZ could be determined by NDVI thereby verifying MZ. This would allow producers to adjust newly delineated zones without having to wait for grain yields. Green NDVI readings were collected across three previously delineated MZ at three site years at the V8, V12, and V16 maize growth stages. Supplemental sampling was also conducted for site year 3 to determine if SPAD chlorophyll and plant height variables expressed MZ differences. Results show that the prototype active sensor did not record NDVI values that were associated with MZ. However, SPAD chlorophyll measurements were associated with MZ and may be a good tool for verifying newly delineated MZ.

The second study objective was to evaluate and compare two commercially available active sensors in determining N variability in maize under greenhouse and field conditions. Climatic and management variables may affect NDVI readings. Two active sensors (Crop Circle™ amber sensor and GreenSeeker™ red sensor) were compared under greenhouse conditions across crop, environmental and management variables including maize plant growth stage, wind, maize crop row spacing, sensor movement speed across the canopy and N fertilizer application rate. Results show that wind had no effect on the NDVI of either active sensor. Nitrogen application rate and maize growth stage did affect NDVI of both sensors with the NDVI values generally increasing with increased N application rate and advancing maize growth stage. The sensor produced NDVI values had the highest linear relationships with applied N at the V12 maize growth stages. Rapid sensor speed resulted in significantly lower NDVI values from red sensor, however, the amber sensor NDVI readings were not affected by sensor movement speed.

Amber and red sensors were then evaluated in maize under field conditions. We also wanted to determine if variables such as soil $N0_3$ concentration, maize leaf N concentration, SPAD chlorophyll and plant height used in conjunction with NDVI could increase NDVI associations with yield when used in a multiple regression. Results show that each sensor's NDVI readings had high R^2 values with applied N rate and yield at the V12 and V14 maize growth stages. However, no single or multiple regression using ancillary variables substantially increased the R^2 of NDVI alone. Overall the amber and red sensors distinguish differences in plant N status and growth stage differences equally under greenhouse and field conditions. The differences observed between active sensors are not substantial and either would be a good tool for the determination of N variability in maize.

Our third study objective was to develop a maize in-season N recommendation algorithm. Algorithms were created for use at the V12 maize growth stage for both the amber and red sensors using the NDVI response index concept. These algorithms yielded similar N recommendations that were not significantly different across sensor type suggesting that the amber and red sensors again performed equally. Also, each N recommendation algorithm yielded unbiased N recommendations suggesting that each was a valid estimator of required N at maize growth stage V12.

Overall the NTech GreenSeeker™ red sensor and the Holland Scientific amber Crop Circle™ sensors performed well in the determination of N variability in irrigated maize and could be very important tools for determining in-season maize N requirements. The integration of these sensors and the appropriate N application algorithms into an on-the-go fertilizer application system could increase the spatial accuracy of N application on fields that are spatially variable if these algorithms are shown to be stable over time and space.

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Spring 2009

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LIST OF ABBREVIATIONS

ARDEC: Agricultural research development and educational center

CV: Coefficient of variation

ECa: Apparent electrical conductivity

GNDVI: Green normalized difference vegetation index

GPS: Global positioning system

ICP: Inductively coupled plasma

INSEY: In-season estimated yield

LAI: Leaf area index

LSD: Least significant difference

MZ: Management zone

N: Nitrogen

NDVI: Normalized difference vegetation index

NIR: Near infrared light

NUE: Nitrogen use efficiency

RI: Response index

SAS: Statistical analysis software

SI: Sufficiency Index

SR: Simple ratio

VIS: Visible light

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CHAPTER 1

Ground based active remote sensors for site-specific management zone verification in irrigated maize production.

ABSTRACT

Precision farming has been a major research focus of agronomists for over a decade. Much of this research has been directed towards enhancing the efficiency of farm inputs without negatively impacting farm profitability and the environment. One way to enhance efficiency is through the adoption of production level management zones (MZ). Previous studies have demonstrated an association of green normalized difference vegetation index (GNDVI) with the N content of maize (*Zea mays*) suggesting that ground-based active remote sensors that determine GNDVI (like NTech Industries' GreenSeeker™ green active sensor) could be quite useful in verifying newly delineated MZ in irrigated maize instead of having to wait for grain yields to verify the MZ. Three site years were examined and sensor readings were collected across three known MZ at the V8 and V12 maize growth stages for site years 1 and 2 and the V8, V12, and V16 maize growth stages at site year 3. Supplemental sampling was also conducted for site year 3 to determine if SPAD chlorophyll and plant height variables verified MZ as well or better than GNDVI. Results show that green GreenSeeker™ sensor produced GNDVI readings are not a good indicator of MZ. The green sensor produces too much variability

to be useful in this capacity. Chlorophyll measurements using the SPAD meter were successful in verifying delineated MZ in-season. Portable SPAD measurements were a good measure of delineated MZ across all maize growth stages tested indicating SPAD readings can be collected anytime for verification purposes which would allow producers to adjust newly delineated MZ without having to wait for grain yields.

INTRODUCTION

Precision farming has been a major research focus of agronomists for over a decade. Much of this research has been directed towards enhancing the efficiency of overall farm inputs (e.g., fertilizers, herbicides, insecticides, water) without negatively impacting farm productivity, profitability and the environment. One way to achieve increased efficiency is through the application of production level management zones (MZ) (Fleming et al., 2004; Koch et al., 2004). The MZs are defined as homogenous sub-regions of a field that have similar yield limiting factors (Doerge, 1999; Khosla and Shaver, 2001). Management zones characterize in-field variability and allow for more efficient application of inputs. By identifying the yield limiting factors, or variability within a field and combining similar areas into zones, the zones can then be managed more accurately and easily leading to increased input efficiency and economic return (Koch, et al., 2004). Soil properties (Mzuku et al., 2005) and plant N uptake (Inman et al., 2005(a)) can vary greatly across MZs. Adopting a management strategy utilizing MZ can lead to optimized nitrogen (N) management for maize (*Zea mays*) production on variable soil types (Khosla et al., 2008 and 2002; Khosla and Alley, 1999.)

The methodology for the delineation of MZ is seemingly unlimited. Any variable or combination of variables known to have an affect on crop yield may be a useful indicator for the delineation of a MZ. Generally MZ are delineated using some combination of bare soil imagery, past yields or farmer experience, field topography or soil surveys, and soil variables such as N content or apparent electrical conductivity (ECa). Numerous studies have been conducted with the goal of delineating the most accurate and effective MZ.

Some studies have focused on soil surveys for MZ delineation as this information is readily available and easily obtained. Franzen et al. (2002) conducted a study to determine if Order 1 or 2 soil surveys (especially digitized surveys) could be used to accurately delineate N management zones for site-specific fertilizer application. This method was compared against grid and topography based zone sampling methods. They determined that Order 1 soil surveys did show similarity between mapping units and N MZs defined by topography. However, the Order 2 surveys did not relate with N management zones. Chang et al. (2004) found that both soil nutrient variability and yield variability must be considered when developing management zones to reduce fertilizer recommendation errors and found that MZ based on a 4-ha grid cell and an Order 1 soil survey showed reduced yield variability (and subsequent reduced fertilizer recommendation errors) compared to delineation methods based on sampling areas impacted by the original homestead separately from the rest of the field, separating the field into grid cells, and using geographic information systems (GPS) or cluster analysis of ECa, elevation, aspect, and variable connectedness to identify zones.

Other studies have focused MZ delineation on past crop yields as information is easily obtained due to the proliferation of yield monitors on modern combines. Cox and Gerard (2007) designed a study to examine the delineation of MZ based on yield stability over a four year period referring to zones as "yield classes" that were categorized as consistent high, consistent average, consistent low, and inconsistent. Cox and Gerard (2007) determined that the yield classes showed no consistent soil or topographical properties that affected yield. Instead it was found that there were unique yield-affecting variables specific to each field. When the appropriate yield-affecting variable was determined yield class was accurately predicted 60 to 100% of the time. Flowers et al. (2005) also studied the possibility of using past multiyear yield data to delineate MZ. The zones delineated using this method was compared with grid soil sampling methods of zone delineation. Several iterations of both past yield data and grid soil sampling were used to delineate MZ. The researchers found that a 68 m grid cell method was the most effective way to describe soil test and nutrient recommendation variability for use with MZ.

Other studies have focused on soil variables for the delineation of MZ. Johnson et al. (2003) performed a study based on ECa for MZ delineation and found a negative correlation with shallow ECa (0-30 cm depth) and winter wheat (*Triticum aestivum*) yield. A positive correlation with deep ECa (0-90 cm depth) and wheat yield within ECa delineated zones was also found. A positive correlation was also observed with deep ECa and maize yield within EC delineated zones. Fleming et al. (2004) compared two delineation methods based on soil properties. The first used bare soil imagery and the farmer's experience with the field. The second used ECa to delineate zones. Fleming et al. (2004) also found that both methods performed well in accurately delineating zones with the accuracy of the ECa method highest in one of the two fields studied. A similar study by Hornung et al. (2006) comparing bare soil imagery based MZ and yield based

MZ was also conducted and found that the bare soil imagery based methods outperformed the yield based MZ delineation methods.

The studies referenced above illustrate the fact that there are a wide variety of methods to delineate MZ. However, all of the studies listed had to verify the accuracy of the delineated zones by comparing the MZs with final crop yield. This shows a limitation of any MZ delineation process. One must wait for harvest to determine if the MZ delineated are correct by determining if crop yield is related to MZ. This makes first year in-season adjustments of the zones impossible to perform and requires producers to continue on with the same management practices throughout the growing season in the hopes that the delineated MZs are correct. One must wait until the next cropping season to make changes due to errors or inaccuracies in the delineation process. It could be of great use to producers if there was a way to evaluate newly delineated MZ early in the growing season so that adjustments could be made if needed. Verification of MZ and the ability to adjust zones could also provide peace of mind for producers who considering adoption of MZ.

Any method used to verify delineated MZ would need to be easy to perform, not be destructive to the crop, and able to be conducted in a timely manner. Remote sensing technologies create the potential to verify MZ early in the growing season while meeting all the criteria mentioned above and several studies have shown that remotely sensed leaf reflectance is related with leaf N content (Alchanatis et al., 2005; Read et al., 2002; Bausch et al., 1998; Bausch and Duke, 1996; Schepers et al., 1996; Blackmer, 1994; Ercoli et al., 1993) which could be a good indicator of MZ.

One particular remote sensing technology that may be used to verify MZ is ground-based active remote sensors (or active sensors) that can calculate normalized difference vegetation index (NDVI). Active sensor produced NDVI is a surrogate measure of parameters used to determine MZ without destroying any part of the crop. The small size and active component ("active" indicates that the sensor has an on board light source for reflectance instead of relying on ambient light like airborne or satellite sensors referred to as "passive") of these sensors allow researchers and producers to use active sensors at their own convenience. Clear skies are not needed, nor are the tasking of airborne or satellite sensors required making active sensors practical and create the potential for use with MZ.

Normalized difference vegetation index 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). There are several active sensors available on the market. Active sensors are relatively small in size and operate by directing sensor produced visible (VIS) light (various wavelengths are used depending on sensor type, manufacturer, and model) as well as near infrared (NIR) light (wavelength 750 – 1300 nm) at the plant canopy of interest. The amount of VIS and NIR light that is reflected off of the plant canopy is collected by the active sensor and a NDVI value is calculated. The VIS (400-720nm) reflectance is primarily dependant on the chlorophyll contained in the palisade layer of the leaf (Campbell, 2002). The NIR reflectance depends on the structure of the mesophyll cells and the cavities between these cells (Campbell, 2002) and a strong linear relationship exists between leaf chlorophyll concentration and leaf N concentration (Ercoli et al., 1993). Therefore, larger maize leaf area and green plant biomass (controlled by chlorophyll content) levels result in higher reflectance and subsequently higher NDVI values.

Numerous studies have shown NDVI to be useful for indirectly measuring crop variables such as photosynthetic efficiency, productivity potential and potential yield across a variety of crops. However to date, the majority of this research has been conducted in wheat and maize. Inman et al. (2007) concluded that NDVI readings from a active GreenSeeker™ red sensor taken at the six to eight leaf maize growth stage had a significant relationship with observed maize grain yield and concluded that active sensor NDVI had the potential to estimate grain yield. Teal et al. (2006) found similar results with the GreenSeeker™ sensor at the V8 growth stage with NDVI / yield linear relationships of $R^2 = 0.77$. Martin et al. (2007) found that coefficient of variation values calculated from NDVI readings related highly with maize grain and biomass yields over a wide array of maize growth stages (from V3 to VT). Freeman et al. (2007) showed that NDVI readings collected at the V8 and V10 maize growth stages can be used in conjunction with plant height measurements to provide valuable information about maize plant biomass production and N uptake which can then be used to direct high resolution N applications with variable rate technology. Thomason et al. (2006) found that NDVI readings collected within the range of maize growth stage V5 to V9 had R^2 values of 0.81 with maize vegetative forage biomass and R^2 values of 0.90 with maize leaf area index (LAI). Clay et al. (2006) conducted a study to determine the affect of water and N stress on NDVI readings. Clay et al. (2006) also discovered that yield losses due to water was related to NDVI ($r = -0.61$) and that NDVI was not related with yield losses due to plant N stress. Osbourne et al. (2004) concluded that green normalized difference vegetation index (GNDVI), where the visible light used for NDVI is the green wavelength (530nm), had the greatest ability to estimate grain yield in the presence of varying N and/or drought stresses in maize.

Research conducted in winter wheat by Girma et al. (2006) found that multiple-linear regression analysis of mid-season NDVI readings, chlorophyll content, plant height, and total N uptake were good predictors of winter wheat yields. Work by Raun et al. (2002) has shown that the use of coefficient of variation (cv) from NDVI readings and a NDVI response index can be used to estimate N application rates based on yield predictions in winter wheat. Using cv an increase in N use efficiency (NUE) of more than 15% was observed over conventional N application methods. Lukina et al. (2001) has shown that the integration of NDVI into N fertilizer algorithms that incorporate predicted yield can greatly increase NUE in wheat.

Other variables may also be good indicators of MZ. Studies conducted by Varvel et al. (2007), Scharf et at. (2006) and Waskom et al. (1996) have found that portable SPAD chlorophyll meters are effective in determining N stress and response in irrigated maize. Nitrogen stress of maize should also be quite different across MZ indicating that a SPAD meter may be a good way to verify MZ. Portable chlorophyll meters such as the Minolta SPAD chlorophyll meter have been shown to adequately diagnose N sufficiency in irrigated maize (Waskom et al., 1996; Blackmer and Schepers 1995).

Studies have also found that plant height can be a good indicator of grain yield in wheat (Girma et al., 2006). Plant height measurements have also been shown to be related to forage biomass production and N uptake in irrigated maize. Freeman et al. (2007) showed high linear relationships ($R^2 = 0.81$) of individual plant height measurements with biomass production across six site years. This relationship should allow for plant height measurements to be used to distinguish MZ as biomass production and N uptake vary across MZ (Inman et al., 2005(a)) due to the growth limiting factors contained within the lower growth potential zones.

The results of past studies suggest that active sensors, SPAD chlorophyll content and plant height should be good indicators of MZ. Therefore a study was conducted to determine if GNDVI values determined by the NTech GreenSeeker™ green sensor verify previously delineated MZ in irrigated maize and to determine if SPAD chlorophyll content and plant height could also be used to verify MZ delineation.

MATERIALS AND METHODS

Study Sites:

This study was conducted in the summer of 2004 and 2005 at three different field locations resulting in a total of 3 site years. Site years 1 (2004) and 3 (2005) were located at the Agricultural Research Development and Education Center (ARDEC) located near Fort Collins Colorado (latitude 40° 40' 38.24" N, longitude 104° 59' 44.76" W). This site is furrow irrigated continuous maize and is classified as a fine-loamy, mixed, superactive, mesic, Aridic Haplustalf (Soil Survey Staff, 1980)

Site year 2 (2004) was located in Yuma Colorado (latitude 40° 08' 48.57" N, longitude 102° 41' 54.03" W) and is continuous maize under center-pivot irrigation. This site is classified primarily as a fine-loamy, mixed, superactive, mesic, Aridic, Argiustoll (Soil Survey Staff, 1981).

Sensors:

Four identical prototype active GreenSeeker™ sensors produced by NTech Industries Inc. were used. The principles and physics behind the operation of these sensors are described in detail in Inman et al. 2005(b). GreenSeeker™ active sensors operate by directing sensor produced VIS light (530 nm) as well as NIR light (770nm) at the plant canopy of interest. The amount of VIS and NIR light that is reflected off of the plant canopy is collected by the active sensor and a normalized difference vegetation index (NDVI) value is calculated. The NDVI equation is presented below:

$$NDVI = (NIR - VIS) / (NIR + VIS) \qquad [Eq. 1]$$

where: NIR = near infrared and VIS = visible light wavelength

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™ sensors produced a green light (530nm) in the VIS spectrum. Therefore, the NDVI value calculated by the green light GreenSeeker™ is referred to as a "green normalized difference vegetation index" or "GNDVI".

Sensor readings were collected across three previously determined MZ. For site years 1 and 2 we attempted to collect GNDVI readings at the V8, V12 and V16 maize growth stages. However, we were only able to collect readings at the V8 and V12 stages for site year 1 and only at growth stage V12 for site year 2. The reasons for this were related to our unfamiliarity with these sensors resulting in software and equipment failure causing us to miss our growth stage window for V16 at site year 1 and for V8 and V16 at site year 2. For site year 3 GNDVI readings were collected across three MZ at the V8, V12, and V16 maize growth stages.

Sensors were mounted on a high-clearance tractor allowing readings to be collected at all maize growth stages of interest. The high-clearance tractor had a hydraulically actuated boom that could be elevated and adjusted to a desired height above the maize canopy. The active sensors were set 100 cm above the maize canopy. This is in the middle of the range (80-120 cm) suggested by the manufacturer's instruction manual (NTech Industries, Inc., 2005). All sensors were connected to a Panasonic Toughbook™ portable computer to record GNDVI values.

Supplemental Sampling and Analysis:

For site year 3 supplemental sampling was conducted at maize growth stages V8, V12, and V16. This sampling was done at the same time that sensor GNDVI readings were collected. The sampling included most mature maize leaf for total N content, maize plant height, soil NO_3-N content, and SPAD chlorophyll readings.

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

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 MZ and were averaged to attain one number per plot replication.

Soil sampling was conducted in each N application plot across all MZ. Samples were collected from ten random locations within each plot and were taken from a depth of 0-20 cm. The ten samples from each plot were then 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 Harris Labs in Lincoln, NE.

Leaf SPAD chlorophyll content readings were collected within each N application rate plot and across all MZ at the same time GNDVI readings were collected. The SPAD chlorophyll meter measures the transmission of red and NIR light through the leaves of the plant. Its readings are strongly related to leaf chlorophyll concentration (Scharf et al., 1996; Markwell et al., 1995) which can reliably indicate N stress and status in maize plants (Scharf et al., 1996; Blackmer and Schepers 1995). These characteristics should allow the SPAD meter to also indicate differences in N status maize across MZ.

Chlorophyll readings were collected from five random most mature leaves in each plot and were averaged to yield one SPAD reading per N application rate plot. SPAD readings were collected using a Minolta SPAD-502 chlorophyll meter.

Maize Grain Yield:

Maize grain yield was determined by a hand-harvest method reported by Inman et al. (2005). Two 1-meter rows of maize were harvested from each plot in each MZ. The grain was then manually removed from each cob and weighed in grams. The moisture and test weight was then determined using a Dickey-John® GAC model 2100 grain analysis computer. The grain weight was then adjusted to 15.5% moisture and scaled to a Mg ha^{-1} yield basis.

Management Zones:

Each site's MZ had been determined prior to the beginning of this study. The MZs had been verified to be accurate in their estimation of productivity from previous studies (Hornung et al., 2006; Mzuku et al., 2005; Inman et al., 2005(a); Khosla et al., 2002). Management zones included high, medium, and low potential productivity. All zones were configured using the soil color method (Fleming et al., 2004). This method of designating MZ uses aerial imagery of soil color, which is directly related to organic matter and soil moisture content (Schreier et al., 1988), as well as the farmer's expertise of the field in question to designate the areas of potential productivity.

Data Analysis:

Data analysis was performed using the Statistical Analysis System (SAS) (SAS Institute, 2006). Our focus was to determine if GNDVI, SPAD chlorophyll and plant height were significantly related to MZ and were therefore, a good indicator of delineated MZ. To accurately accomplish variable comparisons across MZ the effects of N within MZ had to be removed so that only the effects of MZ on the variables were compared. The effects on N within MZ were not of interest. Nitrogen effects within MZ were removed by using the Proc GLM procedure to calculate the data residuals of grain yield, GNDVI, SPAD and plant height. If each variables is good indicator of MZ we would expect to see significant differences in the residuals across MZ as each variable should respond differently within MZ. Analyses of variance of the grain yield, GNDVI, SPAD and plant height data residuals using proc GLM were performed to determine the significant differences of data residuals across MZ.

RESULTS AND DISCUSSION

Maize Grain Yield:

Variability in maize grain yields for each site year across MZ is a good indicator of the accuracy of the MZ. If the MZ are delineated in a manner that accurately describes the variability in the yield limiting factors then maize grain yields should be reflected in the MZ. Statistical analysis of maize grain yield residuals for site year 1 shows the high (6.1 Mg ha^{-1}) and medium (5.6 Mg ha^{-1}) MZs were not significantly different however both were statistically higher than the low MZ (4.8 Mg ha^{-1}) (Table 1.1, Figure 1.1a). These results are typical of other results found with the MZ delineation process used for this site. Khosla et al. (2008) found that intermediate zones were not statistically different from high and low MZs in most cases using this delineation process because the intermediate MZ shares characteristics with both the high and low MZ. It is a much easier and accurate process to distinguish high and low MZ as the variability within these zones is more substantial. The trends observed in yield at site year 1 were also observed at site years 2 (Table 1.1, Figure 1.1b) and 3 (Table 1.1, Figure 1.1c). The residual analysis for grain yield at all three site years suggests that the MZ delineation process accurately characterized the variability located within each field field.

GNDVI:

Green NDVI is a good estimator of maize grain yield under varying levels of N stress (Osborne et al., 2004). We would therefore expect GNDVI readings to fluctuate with maize N and growth variability across MZ because they are delineated based primarily on yield limiting factors. Site year 1 maize growth stage V8 GNDVI readings showed little relationship with MZ. The high, medium, and low GNDVI readings were 0.417, 0.428, and 0.412, respectively (Table 1.2, Figure 1.2a). These values were statistically different; however, the high and low MZ GNDVI readings were significantly lower than the medium MZ. The V12 maize growth stage at site year 3 showed a similar trend in GNDVI readings (Table 1.3, Figure 1.4b). At all other site years and maize growth stages there were no significant differences observed in GNDVI across MZ and there is no discernable trend in the data (Tables 1.2 and 1.3, Figures 1.2a through 1.4c). These results can be attributed to the high amount of variability in the GNDVI values created by the green GreenSeeker™. It appears that the results produced by this sensor are random and are not related with established MZ or maize grain yield. The inability of this sensor to distinguish variability in maize has been confirmed through personal communication with several other researchers who were provided with this proto-type active sensor and with NTech Company officials. Studies have shown that GNDVI is a viable index for use in maize (Osborne et al., 2004; Shanahan et al., 2001); however, the GNDVI vegetation index determined in previous studies was from an airborne multi-spectral platform. The inability of GNDVI to detect maize variability is a reflection of one particular sensor platform, not the index itself.

SPAD Chlorophyll:

Site year 3 V8 maize growth stage SPAD chlorophyll readings across the high, medium, and low MZ were 44.3, 40.0, and 38.4, respectively (Table 1.4, Figure 1.5a). Identical trends in SPAD chlorophyll were observed at maize growth stage V12 (Table 1.4, Figure 1.5b) and maize growth stage V16 (Table 1.4, Figure 1.5c). Values across all three MZ at the V8, V12, and V16 maize growth stages were significantly different and related to MZ. The SPAD meter accurately predicted the previously delineated MZ based on chlorophyll content of the maize leaves at all three maize growth stages measured. This indicates that the leaf chlorophyll content and subsequent N stress varies significantly across MZ at this site from early in the growing season (V8) to late in the vegetative growing season (V16). Our findings support those found by Waskom et al. (1996) that SPAD readings are strongly related to leaf chlorophyll concentration and can reliably indicate N sufficiency and N stress in maize plants. Scharf et al. (2006) reported that chlorophyll meter readings were quantitatively related to yield response N over a wide range of environments and our results support these findings. The SPAD chlorophyll meter is able to detect differences across a wide range of maize growth stages and growing conditions (including those that affect MZ) and could be a valuable tool in the verification of MZ.

Plant Height:

Site year 3 showed no significant differences in measured plant heights at the V8 maize growth stage with heights of 45, 46, and 44 cm across the high, medium, and low MZ, respectively (Table 1.5, Figure 1.6a). Plant height measurements at the V8 maize growth stage may not yet have been affected by the variability that exists between MZ. At this early growth stage the demands on N or water may not yet be large enough to produce differences in plant height. At the V12 maize growth stage plant heights of 116, 111, and 101 cm across the high, medium and low MZ, respectively were observed. Each of these values were significantly different (Table 1.5, Figure 1.7b). By the V12 growth stage, the variability between MZ has affected plant growth leading to significantly taller maize plants in the high zone than in the medium or low MZ. A similar trend was also observed at the V16 growth stage with the high MZ (169 cm) and medium MZ (169 cm) having significantly taller plants than the low MZ (156 cm) (Table 1.5, Figure 1.7c). The high and medium MZ were not significantly different at V16 again demonstrating the difficulty in distinguishing intermediate MZ from the high and low MZ throughout the growing season as shown by Khosla et al. (2008).

Results for site year 3 at the V12 growth stage, and the V16 growth stage to a lesser extent, show that MZ differences can be determined by plant height. Inman et al. (2005(a)) showed that maize N uptake varies greatly across MZ with high productivity MZ generally having significantly greater N uptake than lower productivity MZ and plant height relationships with N uptake (Freeman et al., 2007). Therefore we would expect zones with greater potential for N uptake to have taller plants and vice versa. Our results demonstrate that plant height measurements can be a good verification tool for MZ delineation. However, measuring plant height can be a time consuming process.

CONCLUSIONS

Results indicate that green GreenSeeker™ produced GNDVI readings are not a good indicator of MZ or grain yield differences. This sensor produces too much variability to be useful in this capacity. However, the inability of GNDVI to detect maize variability is a reflection of one particular sensor platform, not the index itself. Portable SPAD chlorophyll measurements were found to relate with delineated MZ for all maize growth stages tested. Plant height measurements were also affected by MZ at the V12 and V16 maize growth stages.

Overall our results suggest that SPAD chlorophyll measurements are the best method to verify newly delineated MZ in-season. Portable SPAD measurements related with delineated MZ at all maize growth stages at site year 3 indicating that readings can be collected anytime prior to tassel for verification purposes. The SPAD readings allow for early and continued verification which could allow producers to change management techniques early in the growing season if necessary. This was not the case with plant height measurements as the differences were observed later in the growing season at the

V12 and V16 growing stages. There are some limitations with the SPAD meter including the time it would take to collect an adequate number of samples throughout a field or MZ. However, the SPAD chlorophyll meter is easy to use, does not destroy the plant, and showed the widest range of applicability in terms of maize growth stage. This suggests that a SPAD chlorophyll meter may be an effective tool for MZ verification in irrigated maize production.

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Table 1.1. Maize grain yield of high, medium and low production level management zones (MZ) at site years 1, 2 and 3.

MZ	Site Year 1	Site Year 2	Site Year 3
	-----------------------	Mg ha^{-1}	-----------------------
High	6.1 a*	12.8 a	9.0 a
Medium	5.6 a	9.5 b	8.4 a
Low	4.8 b	7.2 c	6.8 b

*Different letters indicate significant differences at alpha = 0.10.

Table 1.2. Average GNDVI in the high, medium and low production level management zones (MZ) at the V8 and V12 maize growth stages at site year 1, and the V12 maize growth stage at site year 2.

MZ	Site Year 1 V8	Site Year 2 V12	Site Year 2 V12
	-----------------------	GNDVI	-----------------------
High	0.417 a*	0.422 a	0.696 a
Medium	0.426 b	0.405 a	0.686 a
Low	0.412 a	0.398 a	0.669 a

*Different letters indicate significant differences at alpha = 0.10.

Table 1.3. Average GNDVI in the high, medium and low production level management zones (MZ) at the V8, V12 and V16 maize growth stages at site year 3.

MZ	V8	V12	V16
	-----------------------	GNDVI	-----------------------
High	0.405 a*	0.452 a	0.673a
Medium	0.411 a	0.505 b	0.708a
Low	0.421 a	0.498 b	0.705a

*Different letters indicate significant differences at alpha = 0.10.

Table 1.4. SPAD chlorophyll readings in the high, medium and low production level management zones (MZ) at the V8, V12 and V16 maize growth stages at site year 3.

MZ	V8	V12	V16
	-----------------------	SPAD	-----------------------
High	44.3 a*	43.2 a	47.4 a
Medium	40.0 b	41.5 b	43.7 b
Low	38.4 c	40.6 c	40.4 c

*Different letters indicate significant differences at alpha = 0.10.

Table 1.5. Average maize plant height in the high, medium and low production level management zones (MZ) at the V8, V12 and V16 maize growth stages at site year 3.

	V8	V12	V16
MZ		Plant Height (cm)	
High	45 a	116 a*	169 a
Medium	46 a	111 b	169 a
Low	44 a	101 c	156 b

*Different letters indicate significant differences at alpha = 0.10.

Figure 1.1a. Maize grain yield of high, medium and low production level management zones at site year 1.

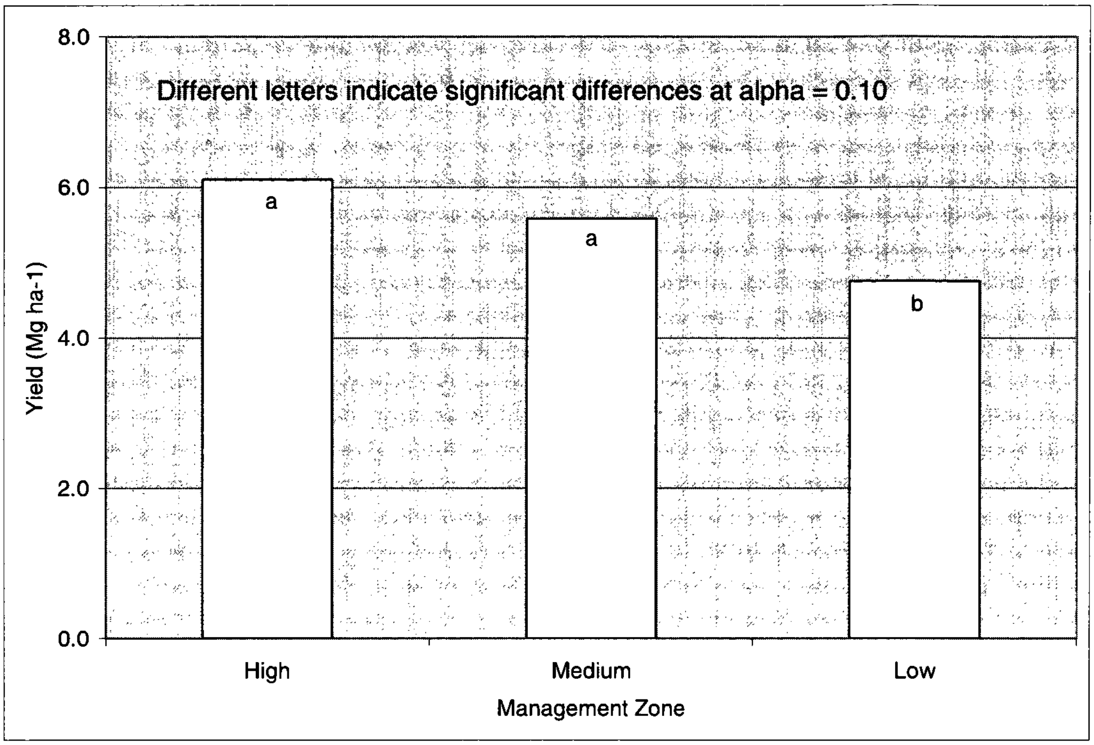


Figure 1.1b. Maize grain yield of high, medium and low production level management zones at site year 2.

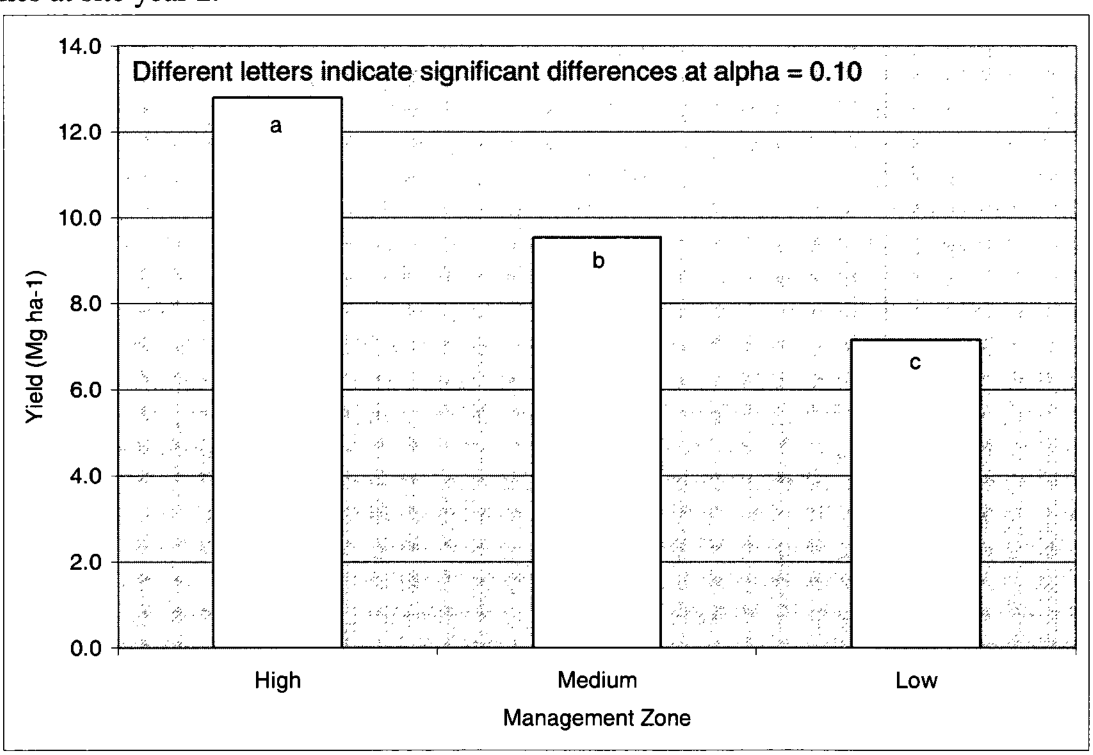


Figure 1.1c. Maize grain yield of high, medium and low production level management zones at site year 3.

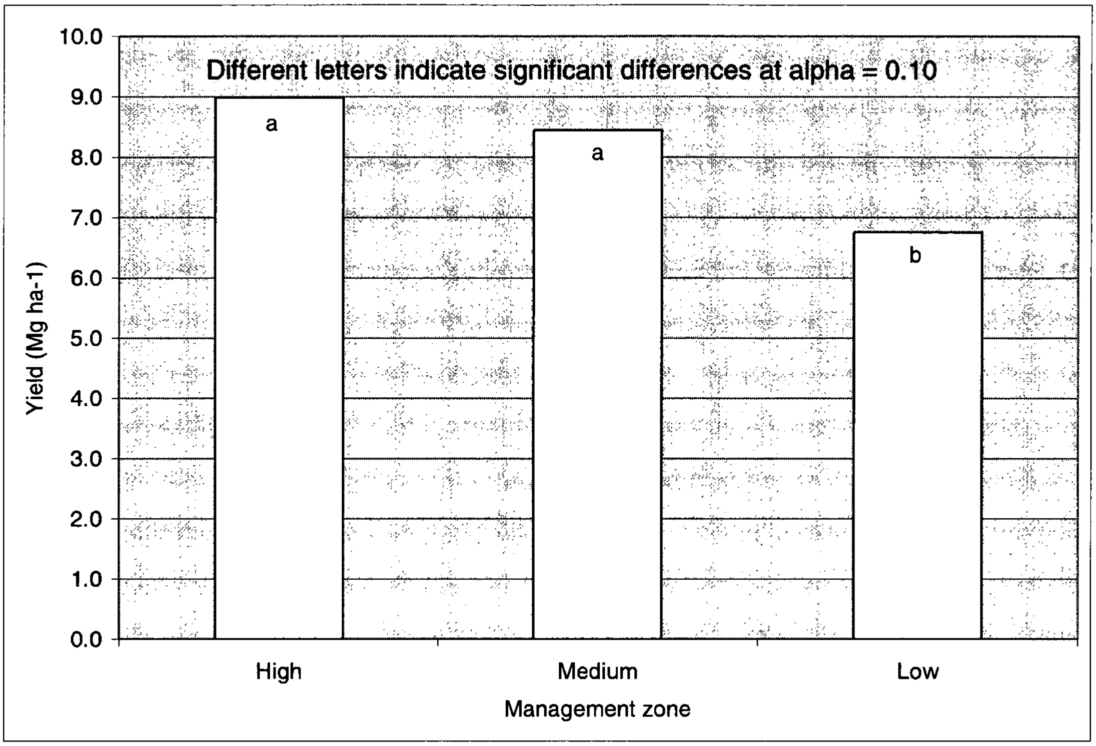


Figure 1.2a. Average GNDVI in the high, medium and low production level management zones at the V8 maize growth stage at site year 1.

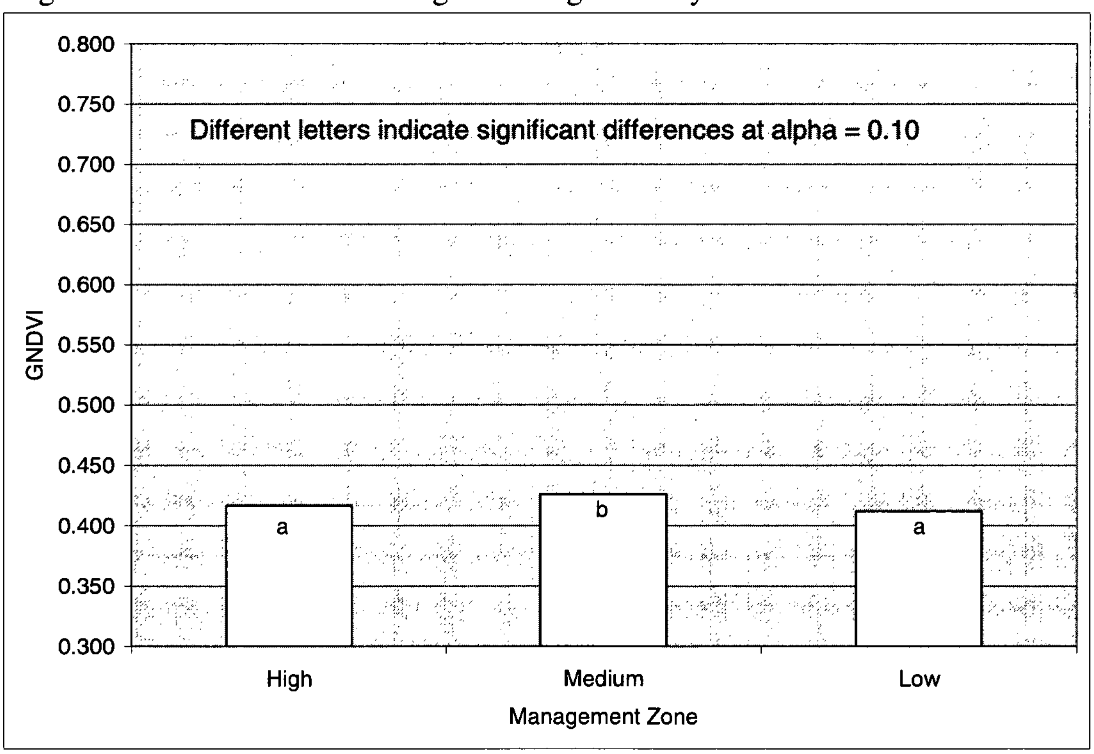


Figure 1.2b. Average GNDVI in the high, medium and low production level management zones at the V12 maize growth stage at site year 1.

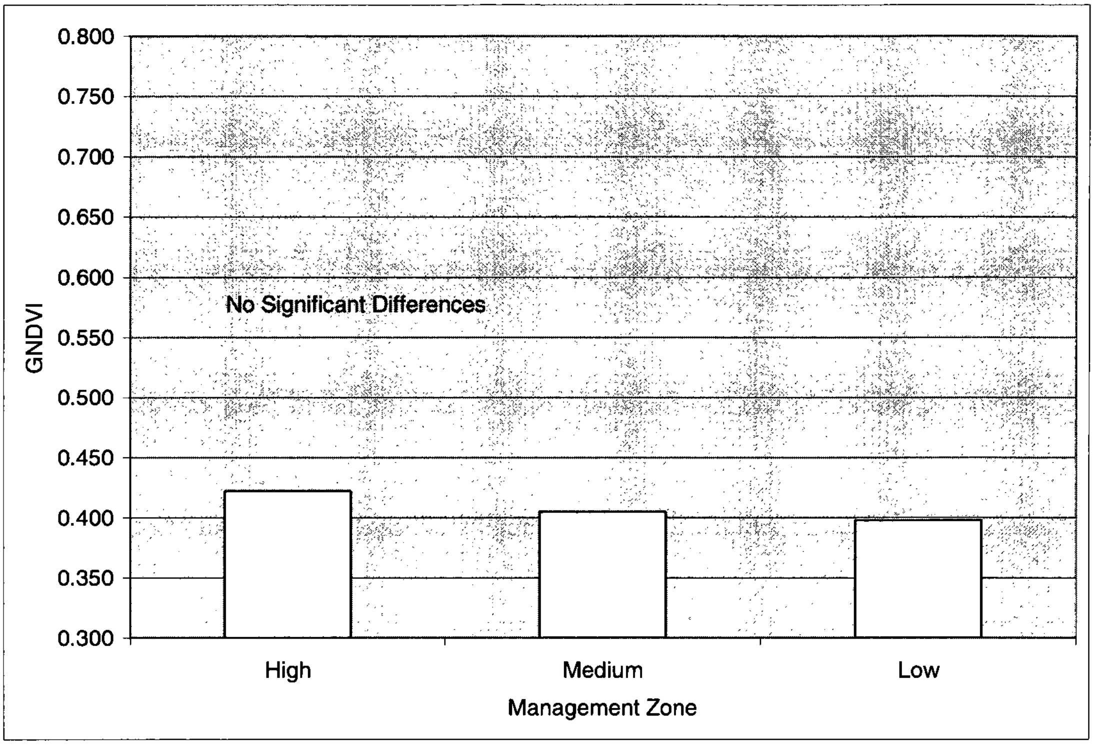


Figure 1.3. Average GNDVI in the high, medium and low production level management zones at the V12 maize growth stage at site year 2.

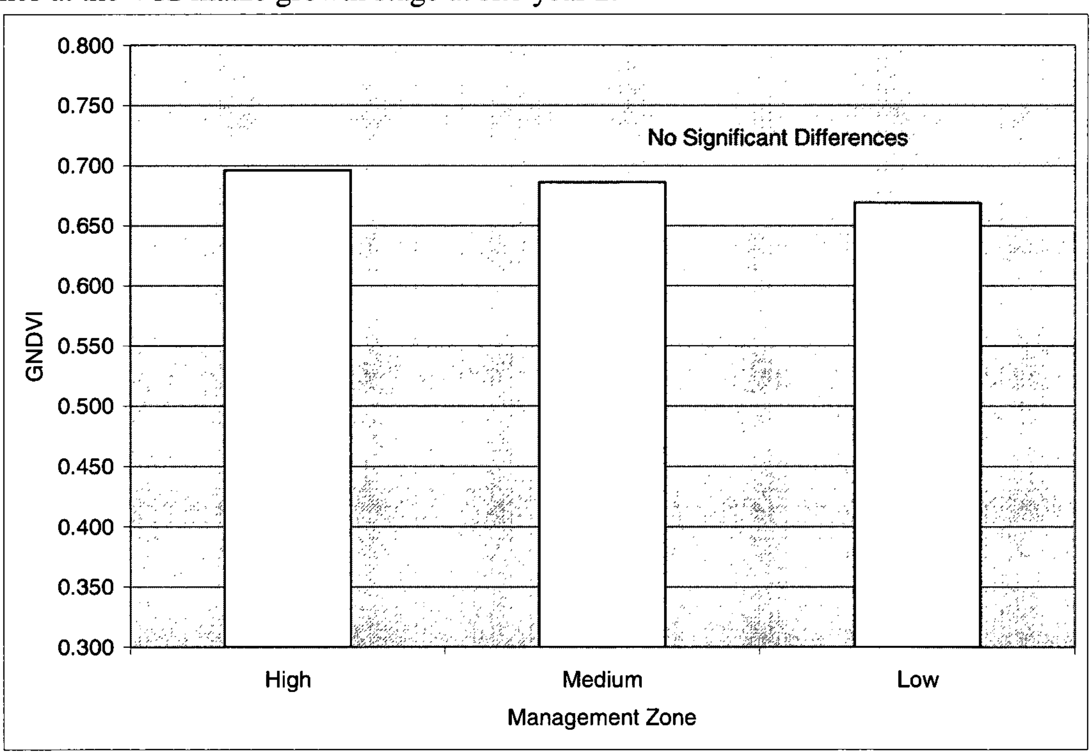


Figure 1.4a. Average GNDVI in the high, medium and low production level management zones at the V8 maize growth stage at site year 3.

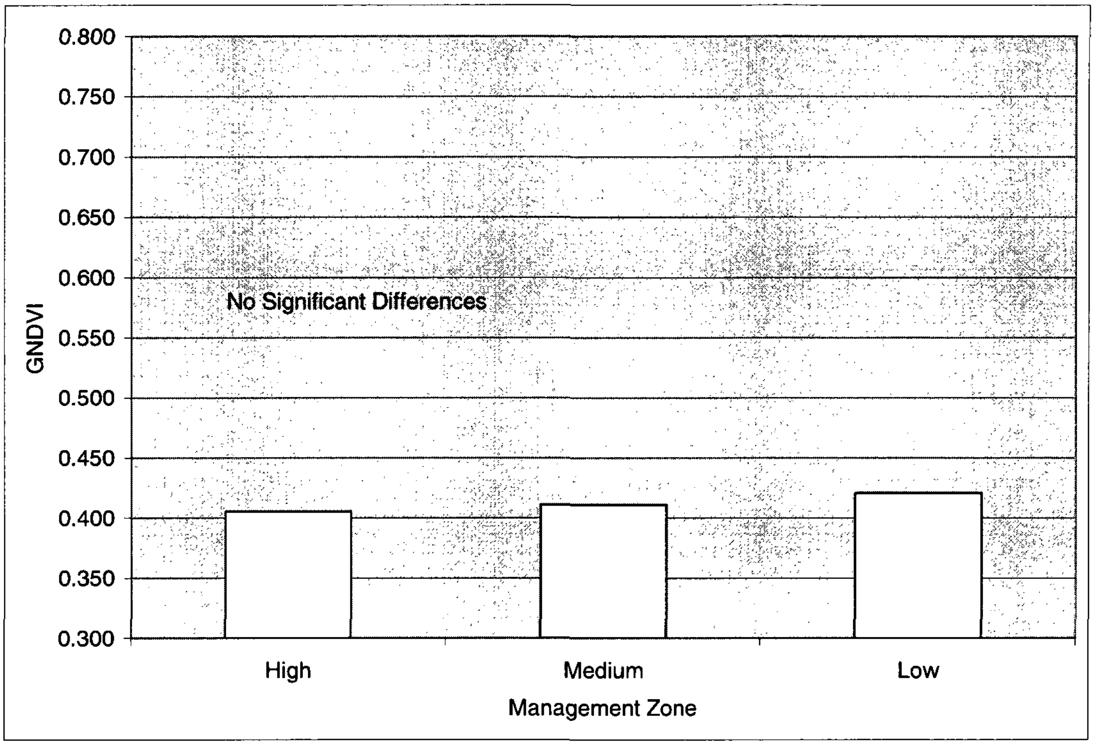


Figure 1.4b. Average GNDVI in the high, medium and low production level management zones at the V12 maize growth stage at site year 3.

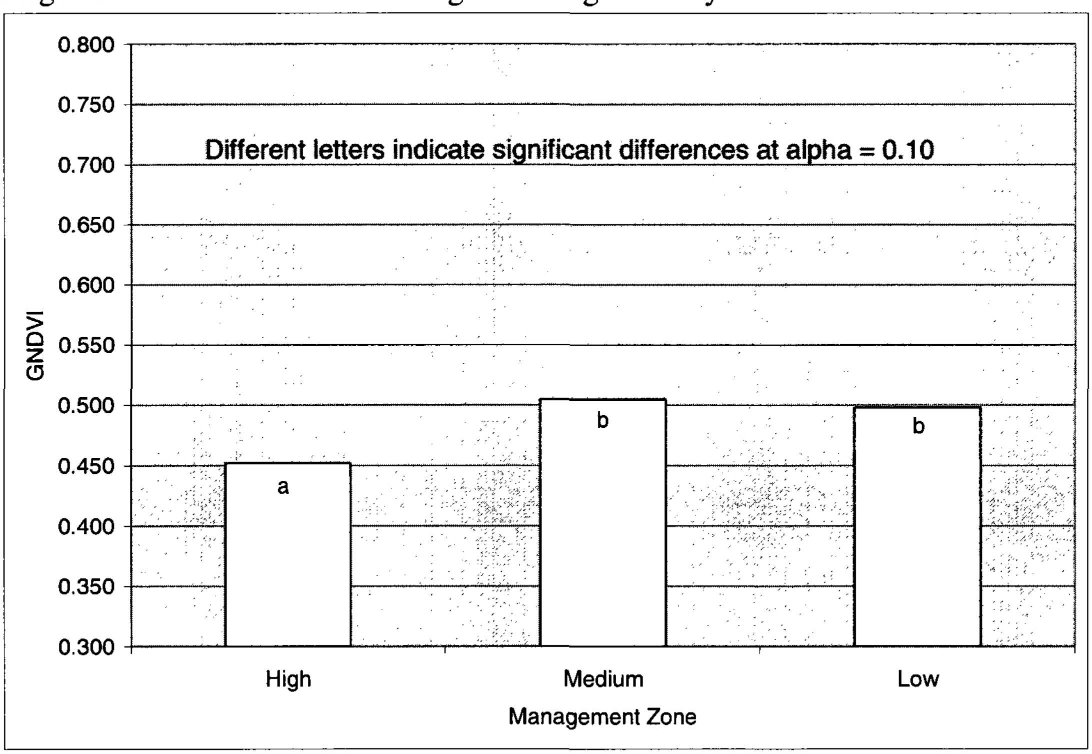


Figure 1.4c. Average GNDVI in the high, medium and low production level management zones at the V16 maize growth stage at site year 3.

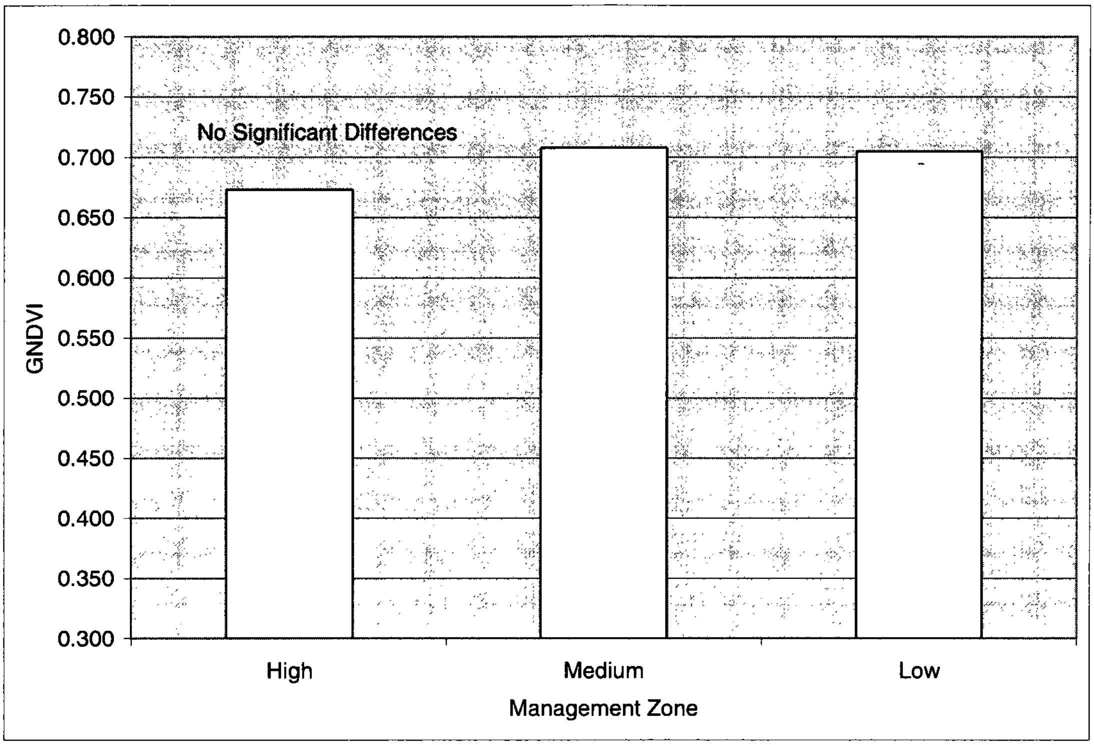


Figure 1.5a. Average SPAD Chlorophyll in the high, medium and low production level management zones at the V8 maize growth stage at site year 3.

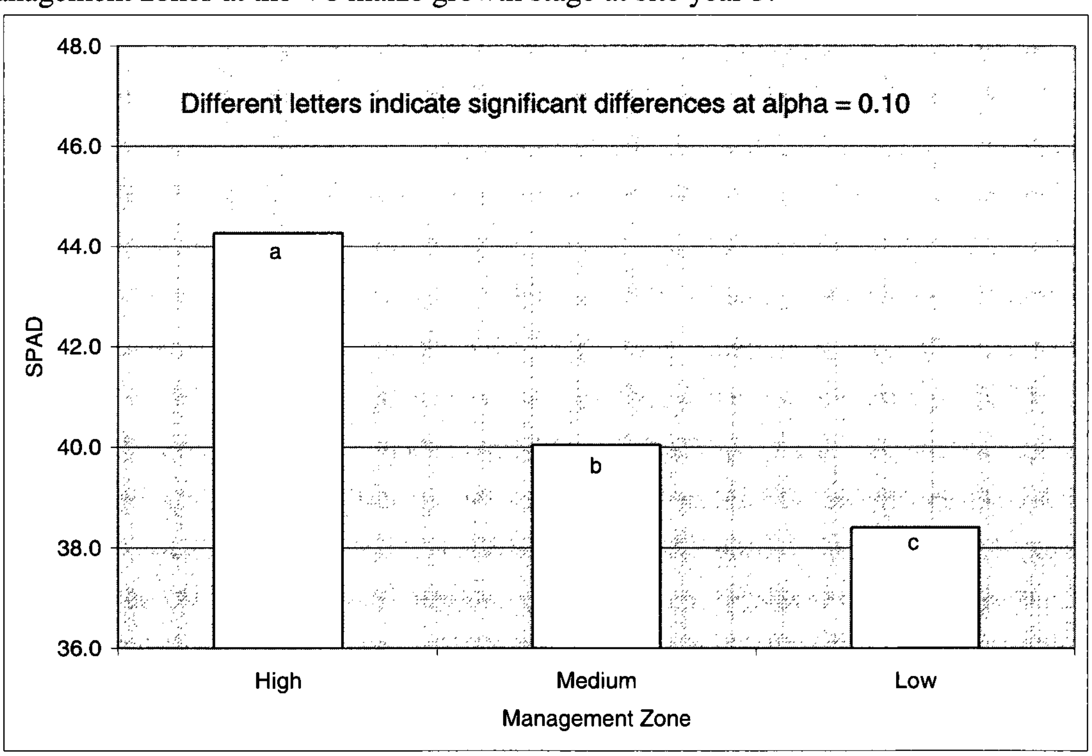


Figure 1.5b. Average SPAD Chlorophyll in the high, medium and low production level management zones at the V12 maize growth stage at site year 3.

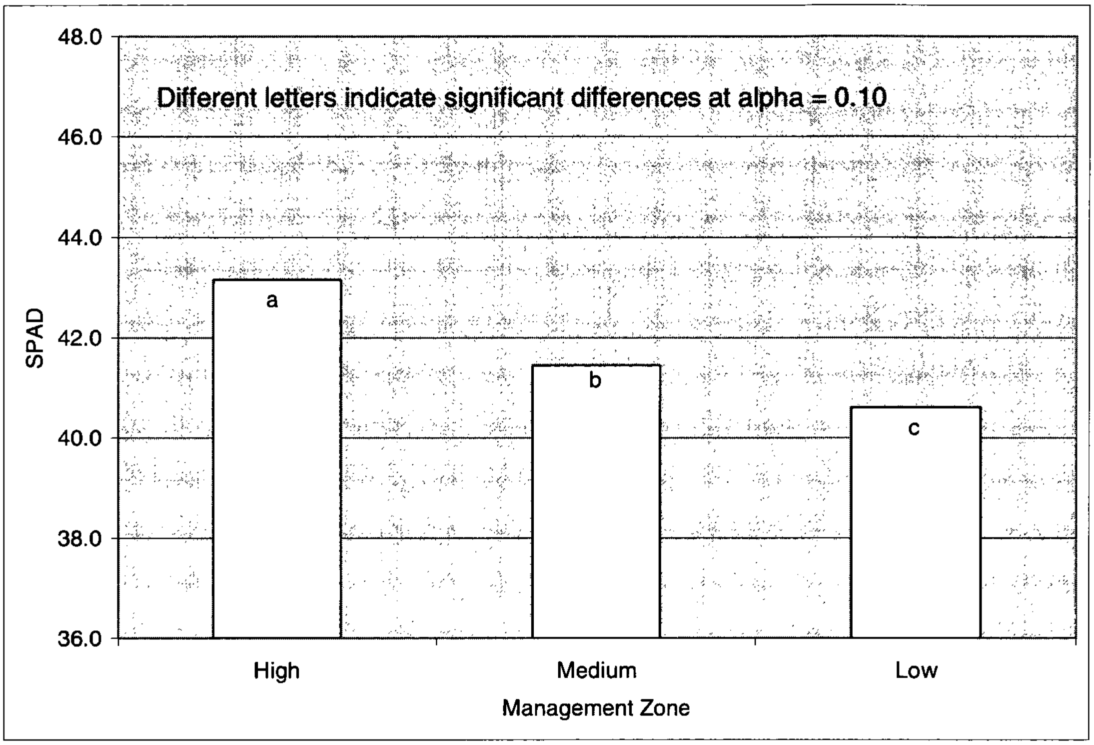


Figure 1.5c. Average SPAD Chlorophyll in the high, medium and low production level management zones at the V16 maize growth stage at site year 3.

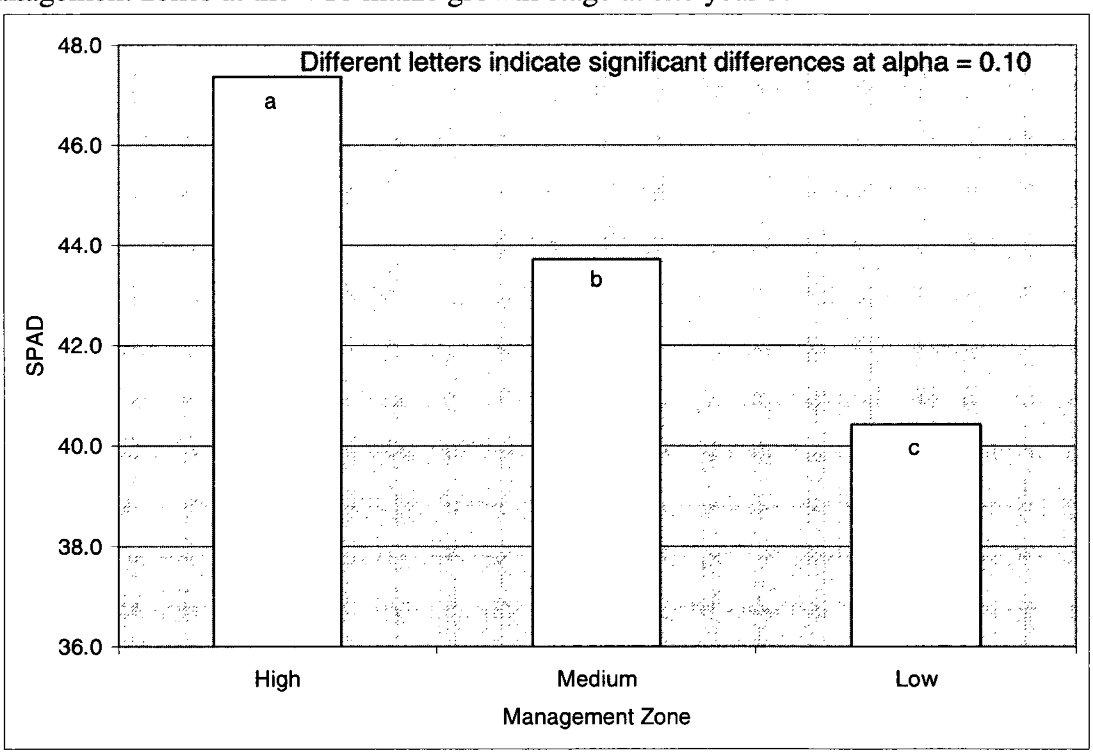


Figure 1.6a. Average maize plant height in the high, medium and low production level management zones at the V8 maize growth stage at site year 3.

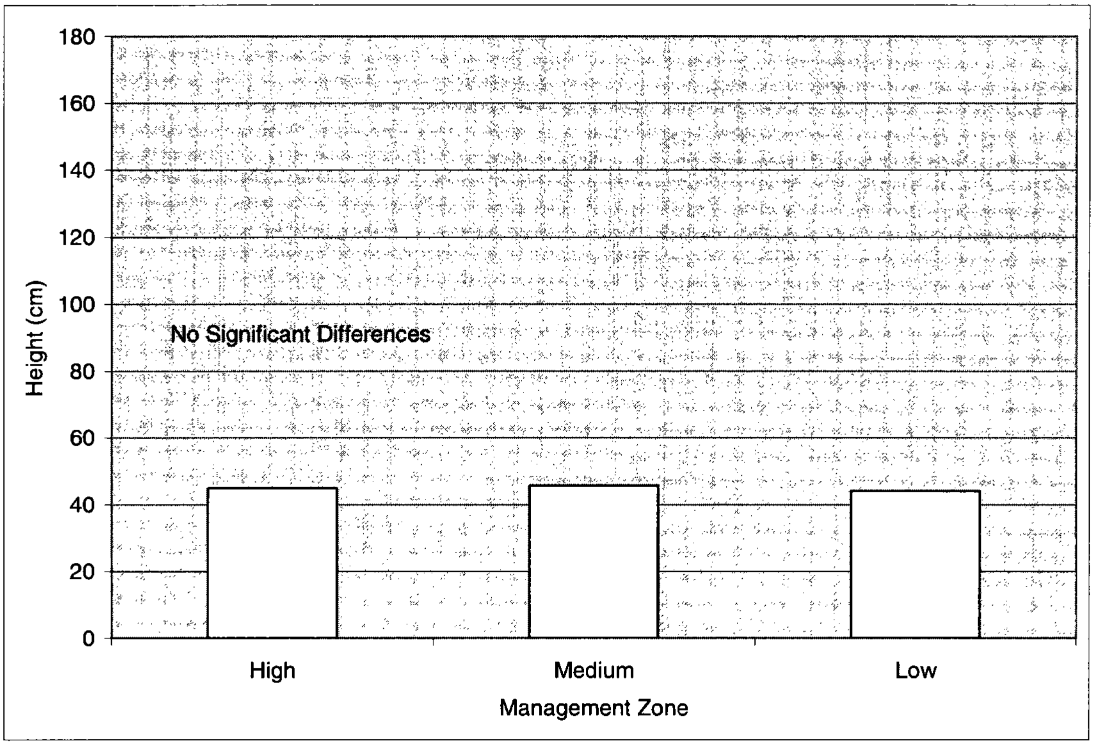


Figure 1.6b. Average maize plant height in the high, medium and low production level management zones at the V12 maize growth stage at site year 3.

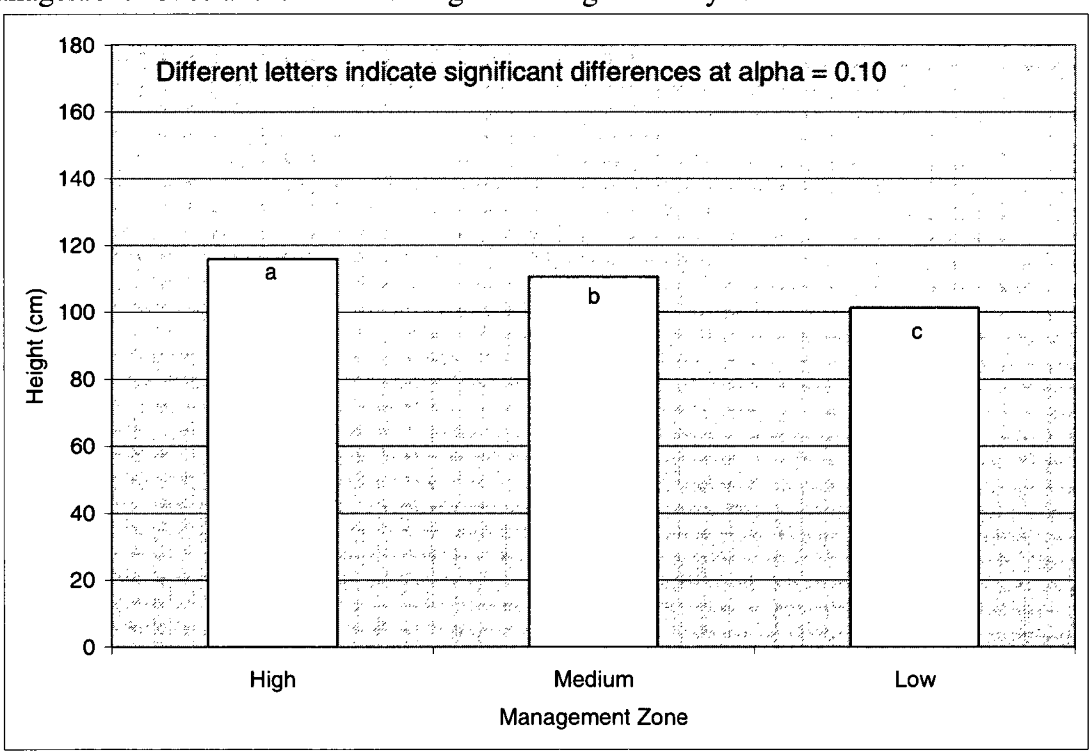
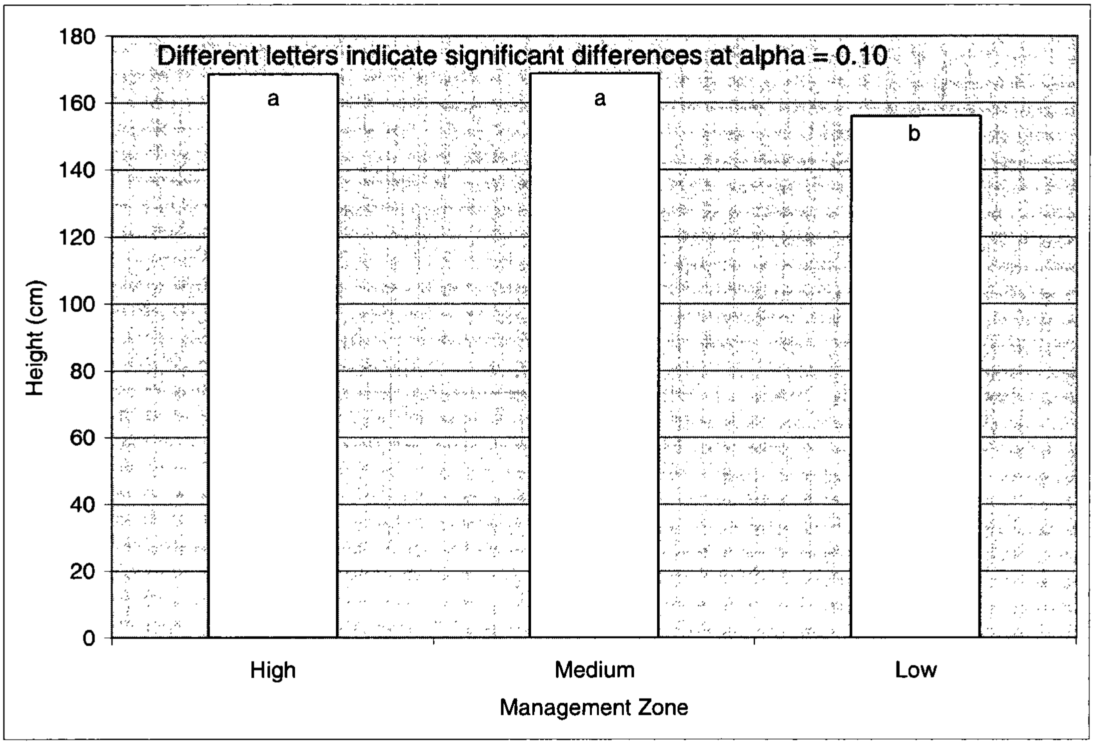


Figure 1.6c. Average maize plant height in the high, medium and low production level management zones at the V16 maize growth stage at site year 3.



CHAPTER 2

Evaluation of two ground-based active remote sensors for N variability determination in maize under greenhouse conditions.

ABSTRACT

A great deal of precision agriculture research has been directed towards enhancing the efficiency of inputs such as nitrogen (N) by quantifying in-field variability. Studies have shown that remotely sensed imagery such as normalized difference vegetation index (NDVI) can determine in-field N variability in maize (*Zea mays*). There are several active sensors that determine NDVI, however, climatic and management variables may affect NDVI readings. Also, the way in which active sensors are used may affect NDVI readings. Our objectives were to determine and compare the effectiveness of two active sensors (Crop Circle™ amber and GreenSeeker™ red) across different crop, environmental and management variables including maize plant growth stage, wind, maize crop row spacing, sensor movement speed across the canopy and N fertilizer application rate under greenhouse conditions. Results show that wind had no effect on the NDVI of either active sensor. Nitrogen application rate and maize growth stage did affect the NDVI of both sensors with NDVI values generally increasing with increased N application rate and advancing maize growth stage. For both sensors the V8 NDVI R^2 values with N rate were lower than those observed at the V10 and V12 growth stages

suggesting that sensor NDVI is most accurate and best used at the V10 to V12 maize growth stage. Sensor speed had an affect on red sensor values. When the red sensor was moved rapidly over the canopy NDVI values decreased compared to slow and stationary movement NDVI. The amber sensor was not affected by sensor movement speed. Overall the amber and red sensors distinguished differences in plant N status and growth stage differences equally in a greenhouse environment. The differences observed between active sensors were not substantial and either would be a good tool for the determination of N variability. It is logical to assume that similar results would be obtained under field conditions.

INTRODUCTION

A great deal of precision agriculture research has been directed towards enhancing the efficiency of inputs such as nitrogen (N) by quantifying in-field variability. Several methods of quantifying variability have proven successful for enhancing N management (Fleming et al, 2004; Khosla et al., 2008, 2002 and 1999), N use efficiency (Raun et al., 2002), and economic return (Koch et al., 2004). Most methods use some form of remote sensing to quantify in-field variability. Numerous studies have shown that airborne remotely sensed imagery can provide valuable information about variability in maize (*Zea Mays*). Shanahan et al. (2001) found that green normalized vegetation index (GNDVI) acquired from an airborne platform during midgrain filling could be used to produce relative maize yield maps depicting spatial variability in fields. Sripada et al. (2005) found that green difference vegetation index (GDVI) acquired with aerial imagery could be used to predict the in-season economic optimum N rate. Scharf and Lory (2002) demonstrated the usefulness of airborne photographs for predicting N sidedress need in maize based on plant color. While useful, airborne or satellite remotely sensed imagery has limitations including cost and the timeliness in which imagery can be acquired, due to satellite/airborne availability, weather, etc. One way these limitations can be overcome is to use ground-based active remote sensing devices (or active sensors) to calculate normalized difference vegetation index (NDVI).

Normalized difference vegetation index is a broadband index that is highly related to leaf area index (LAI) and green biomass (Penuelas et al. 1994), and therefore, photosynthetic efficiency (Aparicio et al., 2002). Several active sensors are available ("active" means the sensors create their own light for reflectance instead of relying on ambient light as is used in airborne or satellite sensors labeled as "passive"). Active sensors are relatively small in size and operate by directing sensor produced visible light (VIS) (various wavelengths are used depending on sensor type, manufacturer, and model) as well as near infrared (NIR) light at the plant canopy of interest (in this case maize). The amount of VIS and NIR light that is reflected off of the plant canopy is collected by the active sensor and a NDVI value is calculated. The VIS (400-720 nm) reflectance is primarily dependant on the chlorophyll contained in the palisade layer of the leaf (Campbell, 2002). The NIR reflectance depends on the structure of the mesophyll cells and the cavities between these cells (Campbell, 2002) and a strong linear relationship exists between leaf chlorophyll concentration and leaf N concentration (Ercoli et al., 1993). Therefore, higher maize leaf area and green plant biomass (controlled by chlorophyll content) levels result in higher reflectance and higher NDVI values. Studies by Alchanatis et al. (2005), Osborne et al. (2002) and Schepers et al. (1996) have all shown this to be the case with leaf reflectance having a significant linear relationship with leaf N content as well as N and water stress in maize (Clay et al., 2006; Osborne et al., 2004).

Active sensors allow for the determination of NDVI at specific times and locations throughout the growing season without having weather or flight concerns. The commercially available active sensors that determine NDVI have been evaluated primarily in winter wheat (*Triticum aestivum*) and maize. Inman et al. (2007) concluded that NDVI readings from a active GreenSeeker™ red sensor taken at the six to eight leaf maize growth stage had a significant relationship with observed maize grain yield and concluded that the red sensor had the potential to estimate grain yield. Teal et al. (2006) found similar results with the GreenSeeker™ sensor at the V8 growth stage with NDVI / yield R^2 values of 0.77. Martin et al. (2007) found that coefficient of variation values calculated from NDVI readings related highly with maize grain and biomass yields over a wide array of maize growth stages (from V3 to VT). Freeman et al. (2007) showed that NDVI readings collected at the V8 and V10 maize growth stages used with plant height measurements can be used to provide valuable information about maize plant biomass production and N uptake which can then be used to direct high resolution N applications with variable rate technology. Thomason et al. (2006) found that NDVI readings collected within the range of maize growth stage V5 to V9 had R^2 values with maize vegetative forage biomass of 0.81 and R^2 values with maize leaf area index of 0.90. Clay et al. (2006) conducted a study to determine the affect of water and N stress on NDVI readings. They discovered that yield losses due to water stress are related to NDVI (r = -0.61) and that NDVI was not related with yield losses due to N deficiency. Osborne et al. (2004) concluded that green normalized difference vegetation index (GNDVI), where the visible light used for NDVI is the green wavelength (530nm), had the greatest ability to estimate grain yield in the presence of varying N and/or drought stresses in maize and that other spectral radiance measurements related well with other maize crop variables such as phosphorus (P) (Osborne et al., 2002).

Research conducted on winter wheat by Girma et al. (2006) found that multiple-linear regression analysis of mid-season NDVI readings, chlorophyll content, plant height, and total N uptake were good predictors of winter wheat yields. Work by Raun et al. (2004 and 2002) has shown that the use of coefficient of variation from NDVI readings and a NDVI response index can be used to estimate N application rates based on yield predictions in winter wheat. Using this method an increase in nitrogen use efficiency (NUE) of more than 15% was observed over conventional N application methods. Lukina et al. (2001) has shown that the integration of sensor NDVI based N fertilizer algorithms based on predicted yield can greatly increase NUE in wheat. The studies listed above illustrate the ability of active sensors to distinguish in-field N variability in maize. While it is well established that active sensors perform this task adequately there are external factors that may affect the ability of active sensors to perform accurately in terms of determining plant N variability. Due to the nature of active sensors there are variables inherent to the location/field where the active sensor is used that may affect NDVI readings such as wind conditions or maize row spacing width. Also, there can be active sensor use variables that can be introduced by the operator that may affect NDVI readings such as movement speed over the canopy. Hodgen et al. (2004) studied sensor positioning over the maize canopy by comparing nadir and 45° off nadir positioning of the active sensor and Solari et al. (2004) showed that light conditions and leaf wetness had no affect on NDVI readings using GreenSeeker™ (red VIS light) and Crop Circle™ (amber VIS light) sensors. Other studies such as Hong et al. (2006) compared several types of sensors including the GreenSeeker™ red sensor and a passive version of the Crop Circle™ and found that both sensors can provide a nondestructive, real-time assessment of apparent plant N status and can be used to direct in-season N-management decisions. Moges et al. (2004) compared red NDVI and green NDVI in winter wheat and found that both performed equally well when predicting forage N uptake, grain yield and grain N uptake. Red NDVI did appear to be a better predictor of forage biomass in winter wheat. The literature contains few comparisons of active sensors or sensor movement speed, climatic variables such as wind, or management variables such as row spacing.

Wind and maize row spacing variables may affect NDVI readings when used in irrigated maize. The two variables are related in that they can affect the amount of reflected light being returned to the active sensor. The amount of biomass and LAI influence reflectance and subsequently NDVI. With wider in-row plant spacing the reflectance and NDVI should decrease compared to narrower in-row plant spacing. It is feasible that wider maize in-row spacing may not have a high enough level of canopy closure to allow the active sensor to perform accurately due to increased background interference from the soil and simply not enough leaves for adequate reflectance of the senor produced light. It is also possible that wind could affect sensor accuracy. As wind velocity increases the leaves necessary for reflectance will be displaced. This could affect sensor light reflectance and subsequent NDVI readings because a moving leaf may have a different amount of reflectance than a stationary leaf.

Sensor use or application variables may also affect active sensor NDVI readings. The movement of active sensors over the maize canopy could affect sensor light reflectance and NDVI readings. As speed increases across the canopy, the active sensor's stability may be compromised. This could alter accuracy in determining NDVI differences. This is a concern when you consider the two primary ways in which active sensors are used, are by walking and by mounting on a tractor. Obviously, these two methods differ greatly in sensor speed over the maize canopy.

Another factor that may affect NDVI determination is the active sensor itself. There are several active sensors commercially available. Two of the primary models are the NTech Industries GreenSeeker™ red sensor and the Holland Scientific Crop Circle™ amber sensor. Each of these sensors is based on the same scientific principles. A detailed description of the GreenSeeker™ sensor's operation is available in Inman et al., (2005). They differ only in the visible wavelength of light (red or amber) used for canopy reflectance. Although these sensors operate on the same principle, it is quite possible that one sensor may perform the task of NDVI determination better than the other. This could be due to engineering or simply that one wavelength performs better than the other. In any case, the active sensor itself may affect NDVI values and the accuracy of sensing variability.

With all of the above factors in mind a study was conducted to examine how external variables affect NDVI readings. We concluded that the only means of effectively conducting this study would be under greenhouse conditions so that maize row (within and between row) spacing could be manipulated using the same plants for each spacing treatment. This also allowed us to vary wind speeds (artificial wind conditions were produced), which is impossible to duplicate under field conditions. Conducting a greenhouse study also allowed for all variables, other than those of interest, to be kept constant.

The objectives of this study were to evaluate and compare the effectiveness of two active sensors in determining N variability (using NDVI) in maize across different crop variables, environmental variables and management factors.

MATERIALS AND METHODS

Study Site and Soil:

This study was conducted at Colorado State University's Greenhouse Facilities located in Fort Collins, Colorado during the winter and spring months of 2006. The soil used was collected from the top 30 cm of a furrow irrigated continuous maize field located at Colorado State University's Agricultural Research Development and Education Center (ARDEC) located near Fort Collins, Colorado (latitude 40° 40' 38.24" N, longitude 104° 59' 44.76" W). The study soil was classified as a fine-loamy, mixed, superactive, mesic, Aridic Haplustalf (Soil Survey Staff, 1980). After collection, soil analysis was performed for residual NO_3-N content by Harris Labs in Lincoln, NE. (Mulvaney, 1996) and it contained 9 mg kg^{-1} residual NO_3-N.

Sensors:

Two active sensors were tested and compared. The sensors tested included the red GreenSeeker™ Model 505 hand held optical sensor manufactured by NTech Industries Inc. and the Holland Scientific Crop Circle™ ACS-210 Plant Canopy Reflectance Sensor. The principles and physics behind the operation of these sensors are described in detail by Inman et al. (2005). The red GreenSeeker™ Model 505 sensor operates by directing sensor produced visible light as well as near infrared (NIR) light (wavelength 770 nm) at the plant canopy. The amount of visible and NIR light that is reflected off of the plant canopy is collected by the active sensor and a NDVI value is calculated. The NDVI equation is presented below:

$$NDVI = (NIR - VIS) / (NIR + VIS) \qquad [Eq.1]$$

where: NIR = near infrared and VIS = visible light wavelength

This 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 red GreenSeeker™ generates a red light (wavelength 660 nm). Therefore, the index calculated from the red GreenSeeker™ sensor will be referred to as "Red NDVI".

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

Sensor readings were collected across four N application rates at the V8, V9, V10, V11, and V12 maize growth stages. The red sensor was placed 100 cm above the maize canopy for all readings. This is in the middle of the range (80-120 cm) suggested by the manufacturer's instruction manual (NTech Industries, Inc., 2005). The amber sensor was placed 70 cm above the maize canopy as readings were collected. This was the middle of the manufacturers suggested height range (50-90 cm) for this sensor (Holland Sci., 2005). The red sensor was connected to a Compaq Ipaq™ hand-held computer to record NDVI values. The amber sensor was connected to Holland Scientific's GeoSCOUT GLS-400 data logger (Holland Sci., 2006) to record all NDVI values.

External Variables:

Our objectives were to evaluate and compare the effectiveness of two active sensors across different crop variables, environmental variables and management factors. These variables and factors included maize plant growth stage, wind, maize crop row spacing, sensor movement speed across the canopy, and N application rate.

Sensor readings were collected by using a custom built scaffold that allowed the active sensors to be positioned at the proper height above the maize canopy at each maize growth stage. This scaffold also allowed the active sensor to be moved over the top of the canopy at different speeds. A tarp was placed at the bottom of the scaffolding and a layer of soil (same soil as in the study pots) was place on the tarp to a depth of approximately 7.5 cm. This created a soil background similar to that of the field best simulating conditions under which active sensors would be performing.

The primary environmental variable of interest was wind speed. We wanted to see if the movement of the maize leaves had any effect on light reflectance and the subsequent NDVI value. To simulate wind an ordinary table fan was used. This fan was placed approximately 1 meter to the side of the potted maize plants at a height where the top of the fan was even with the height of the maize. Two wind speeds were tested; wind and no-wind. The wind treatment was the fan turned on to the medium position creating a cross-wind of 5 m s^{-1} while the NDVI readings were collected.

Since the maize plants were in pots, different maize row spacing could be simulated. By pushing the pots as close together as possible 25 cm row spacing was created, essentially closing the canopy over the top of the soil surface. Pots were also placed at (center pot to center pot) 50 cm and 75 cm row spacing to create three different levels of canopy closure and soil exposure. For each N application rate 15 pots planted with maize were used (each pot had 3 maize plants). This allowed for the simulation of 3 rows of maize each having 5 pots. Each pot was 20 cm in diameter resulting in a row length of 100 cm. Sensor readings were collected along the entire length of the center row for all spacing treatments.

Sensor speed over the canopy was also tested to determine if movement would have an affect on NDVI readings. It is reasonable to expect that the slower active sensors move over the canopy, the higher the association with N status of the maize would be. To test the hypothesis three different speeds were simulated; stationary, slow, and fast. To achieve the stationary sensor positioning each sensor was placed over the middle of the center maize row. Readings were then collected for 10 seconds. To create the slow movement speed active sensors were moved over the top of the maize canopy taking 5 seconds to traverse the 100 cm row. This equates to a velocity of 0.20 m s^{-1} (0.72 km h^{-1}). To create the fast movement speed each active sensor was moved over the 100 cm maize row in 1 second. This equates to a velocity of 1 m s^{-1} (3.6 km h^{-1}). This created treatments, with 10 seconds of NDVI data (stationary), 5 seconds of NDVI data (slow), and 1 second of NDVI data (fast) over the same general area of the maize canopy.

Four N application rates were used (0, 75, 150, and 225 kg ha^{-1} equivalent), allowing for a graduated N response from the maize plants. This, in combination with the other variables created 216 possible conditions (4 N rates x 3 row widths x 2 wind speeds x 3 sensor speeds x 3 maize growth stages) for each sensor to be tested across. Every possible interaction of the aforementioned variables for each maize growth stage was created for NDVI readings.

Plants:

Maize plants were grown in plastic pots measuring 20 cm in diameter and 21.25 cm in height. Each pot contained 6 kg of soil. Fifteen pots for each N rate (0, 75, 150, and 225 kg ha^{-1}) were planted resulting in a total of 60 pots. Prior to planting, supplemental reagent grade nutrient materials were mixed individually for each pot to meet plant nutrient requirements using an industrial grade rotating soil mixer. All pots received 500 mg P pot^{-1} (potassium phosphate) and 636 mg K pot^{-1} (potassium phosphate). Nitrogen was also mixed prior to planting as ammonium nitrate at the appropriate levels; 0 mg pot^{-1}, 778 mg pot^{-1}, 1557 mg pot^{-1}, and 2335 mg pot^{-1}, for the 0, 75, 150, and 225 kg ha^{-1} N rates, respectively. Five maize seeds (Pioneer *cv* 38P05) were planted in each pot. Ten days after emergence each pot was thinned to 3 plants each. The pots were watered regularly and maintained as close as possible to field capacity throughout the study. The maize plants were allowed to grow until growth stage V12 (approximately two months). Maize growth stages beyond V12 were too tall for the scaffolding and no longer allowed the sensors to be placed at the proper heights above the canopy for accurate NDVI readings. At this time study was halted. At the V12 growth stage 5 random most mature leaves from each pot were collected and analyzed for total N content by 2% acetic acid digestion and inductively coupled plasma (ICP) spectrometry.

Data Analysis:

All statistical analysis was performed using the Statistical Analysis System (SAS) (SAS Institute, 2006). Analyses of variance were conducted using the ANOVA procedure for tests of all main effects and interactions. The option Means in the ANOVA procedure was used to attain all mean values and main effects least significant differences (LSDs). Significant interaction ($P \leq 0.05$) LSDs for mean separation were also calculated. All regressions were performed using the Reg procedure in SAS. Due to the large quantity of NDVI readings (over 25,000 NDVI data points) the data was "bootstrapped" prior to regression analysis. Bootstrapping reduced each N treatment within row spacing data set from approximately 250 data points to 20 data points while maintaining the overall variance in the data. This process made analysis more manageable and also reduced the possibility of creating false significant interactions that can occur when analyzing such large data sets. Segmented regression was conducted using the Proc NLIN procedure in SAS for the instances where N response reached a plateau.

RESULTS AND DISCUSSION

Amber Sensor:

Results for the amber sensor were analyzed using a 3 factorial (N application rate x maize growth stage x maize row spacing) design (Table 2.1). However, the results will be examined by evaluating the R^2 of amber NDVI with applied N rate at each maize growth stage within maize row spacing because row spacing will not change under normal field conditions. The amber sensor recorded significantly different NDVI levels at each of the three maize row spacing variables tested with narrower row spacing resulting in higher amber NDVI values (Table 2.1). Higher amber NDVI values result when maize plants are in close proximity to each other creating more canopy closure. This is also the case when N application rate increases and maize growth stage advances which also lead to significantly higher NDVI values with the amber sensor.

Red Sensor:

The red sensor was analyzed using the same 3 factorial design as the amber sensor (Table 2.2). As with the amber sensor the red sensor recorded significantly higher NDVI values at narrower row spacing, higher N application rates and advancing maize growth stages due to increased LAI and biomass and subsequent higher reflectance. Our results correspond with the results of other studies where NDVI increases with increased LAI (Aparicio et al., 2002 and 2000), biomass (Martin et al., 2007; Thomason et al., 2007; Teal et al., 2006) and leaf N content (Alchanatis et al., 2005).

NDVI, Row Spacing and Applied N Rate:

Previous studies have shown that NDVI has high R^2 values with increased maize height and biomass (Freeman et al., 2007) and leaf N concentration (Alchanatis et al., 2005). Therefore, we would expect NDVI to decrease with wider row spacing, and NDVI to increase with increasing N application rate. No studies have been reported that determine how different sensors compare within different maize row spacing widths. This information could be valuable to producers that are trying to determine which sensor to adopt based on how active sensors determine N variability within particular management variables such as maize row spacing.

25 cm Maize Row Spacing:

At 25 cm maize row spacing R^2 values of NDVI with applied N rate were calculated at the V8, V10 and V12 maize growth stages for both the amber (Figure 2.1a) and red (Figure 2.1b) sensors. No significant differences in NDVI were observed at the V10 or V12 maize growth stage between the 150 and 225 kg ha^{-1} applied N rates for either sensor (Tables 2.1 and 2.2). The plants are large and close enough at the 150 and 225 kg ha^{-1} rates at V10 that maize canopy closes and the active sensors cannot determine a difference in the applied N rates. At the V8 growth stage significant differences are present between all applied N rates for both sensors (Tables 2.1 and 2.2) and the plants are small enough at V8 that canopy closure is not reached. Therefore, a simple linear regression is used at the V8 growth stage and a segmented regression with a plateau is used above 150 kg ha^{-1} applied N at the V10 and V12 growth stages. Because there is no difference between the 150 and 225 kg ha^{-1} rates at V10 and V12 we would expect sensors to record similar NDVI readings at both rates resulting in a plateau, therefore, we used a linear plateau model for analysis. The linear plateau model has been used by other researchers including Varvel et al. (2007) when N response in maize has reached a plateau

The highest R^2 values of NDVI with applied N rate were found at the V10 and V12 maize growth stages for both sensors. The amber sensor had an NDVI $R^2 = 0.86$ with N rate at both V10 and V12 (Figure 2.1a). The red sensor had very similar values with $R^2 = 0.84$ for both V10 and V12 (Figure 2.1b). The red sensor records NDVI values at a higher range than the amber sensor. This is simply a function of the mechanics of each sensor, the NDVI range did not affect the results observed for either sensor. At the

V8 maize growth stage the amber and red sensors had a lower linear relationship with N rate ($R^2 = 0.71$ amber, $R^2 = 0.13$ red) than at the V10 or V12 growth stages suggesting that at V8 the differences in plant growth as affected by N application rate may be too small for active sensors to accurately detect and that one should wait until at least the V10 maize growth stage to optimize the potential of these sensors. Overall at the 25 cm row spacing each active sensor's NDVI had very similar, and relatively high R^2 values with applied N rate at the V10 and V12 maize growth stages suggesting that both sensors perform adequately at 25 cm row spacing. However, when looking at Figures 2.1a and 2.1b one can see that the red sensor does have more variability in the NDVI readings within each N rate than does the amber sensor. This creates the potential for more error with the red sensor.

50 cm Maize Row Spacing:

At 50 cm maize row spacing linear plateau regression was performed only at the V12 maize growth stage between the 150 and 225 kg ha^{-1} N application rates for both active sensors. Amber sensor NDVI linear relationships with N rate at 50 cm maize row spacing were very similar to those observed at 25 cm spacing. At the V10 and V12 growth stages $R^2 = 0.83$ (V10) and 0.89 (V12) (Figure 2.2b) were observed. The V8 value was again much lower with an $R^2 = 0.51$ suggesting that V8 is too early to determine differences using active sensors.

The red sensor NDVI had lower R^2 values with applied N rate at 50 cm row width than at 25 cm. The red sensor also had lower R^2 when compared to the amber sensor at 50 cm row width. The V10 and V12 R^2 values were = 0.72 and 0.66 respectively (V8 R^2 = 0.32) (Figure 2.2b). When comparing the two sensors using Figures 2.2a and 2.2b we again see that the NDVI values for the amber sensor have less variability than the red sensor. This could explain the differences in R^2 values. Also, when comparing the variability in NDVI readings across row spacing, NDVI readings for the red sensor had more variability at 50 cm spacing than at the 25 or 75 cm row spacing widths. It is unclear why there is more variability at the 50 cm maize row spacing than at the 25 or 75 cm spacing but suggests that the red sensor may be less stable than the amber sensor.

75 cm Maize Row Spacing:

For the 75 cm maize row spacing simple linear regression for maize growth stages V8 and V10 was used and segmented regression was used above 150 kg N ha^{-1} at the V12 maize growth stage. Results for the 75 cm row spacing are listed in Tables 2.1 (amber) and 2.2 (red) and show that R^2 values remain very similar to the 25 and 50 cm row widths for the amber sensor with V8, V10 and V12 R^2 = 0.60, 0.86, and 0.88, respectively (Figure 2.3a). The red sensor NDVI values also had high linear relationships with applied N rate at V10 and V12 with R^2 = 0.85 and 0.82 respectively. The V8 R^2 was lower at 0.39 (Figure 2.3b). The variability in red NDVI readings is less than that observed at the 50 cm spacing and the R^2 values rebounded to the levels observed at the 25 cm spacing. However, overall variability in NDVI readings is still greater for the red sensor than for the amber sensor.

The amber sensor was not affected by maize row spacing at the V10 and V12 growth stages maintaining R^2 values in the mid to high eighties across all widths tested. The V8 R^2 values were lower than those at the V10 and V12 growth stages suggesting that this sensor is most accurate and best used at the V10 or V12 maize growth stages after differences in maize growth have had time to materialize. The red sensor results were not as easily interpreted. The red sensor performed well and on par with the amber sensor at the V10 and V12 maize growth stages at the 25 and 75 cm maize row widths. However, at the 50 cm width the R^2 were much lower and there appears to be high variability in the readings. The red sensor also had lower R^2 values at the V8 growth stage suggesting that the red sensor should not be used at until the V10 growth stage. While the amber and red sensors performed equally the variability in the red sensor suggests that the amber sensor may be more stable and reliable under the conditions tested.

Overall the effect of row width on NDVI supports our hypothesis. Our hypothesis (based on the results of past studies) was that NDVI would increase with decreasing row width and NDVI would increase with increasing N rate. Our results support the hypothesis and the findings of past studies such as Aparicio et al. (2002) where increasing LAI and biomass (narrower row width) resulted in increased NDVI. And studies such as Alchanatis et al. (2005) where increased leaf N content due to increased N uptake at higher N application rates also resulted in increased reflectance.

Maize Plant Leaf N Concentration:

Linear relations to determine R^2 were also performed between amber and red NDVI and entire maize plant N, and most mature leaf N concentration. Freeman et al. 2007 reported a strong relationship between NDVI and maize N uptake. Therefore, we would expect NDVI to increase with increased N content. Nitrogen concentrations were determined at the end of the study at the V12 maize growth stage because determining leaf concentration at the other growth stages would have resulted in removing leaves from the plants possibly affecting NDVI results at subsequent growth stages. Results show very similar R^2 values for both entire plant N and maize leaf N with NDVI from both the amber and red sensors. Amber NDVI had an $R^2 = 0.94$ (entire maize plant N) and 0.95 (maize most mature leaf N) while the red sensor R^2 values were 0.92 for both entire plant N and leaf N) (Table 2.3, Figure 2.4a and 2.4b). Results show that there is a very strong relationship between the amount of N in the entire plant and in the leaves and NDVI for both sensors. Visible light reflectance is primarily dependant on the chlorophyll contained in the palisade layer of the leaf (Campbell, 2002). The NIR reflectance depends on the structure of the mesophyll cells and the cavities between these cells (Campbell, 2002) and a strong linear relationship exists between leaf chlorophyll concentration and leaf N concentration (Ercoli et al., 1993). Therefore, higher maize leaf area and green plant biomass (controlled by chlorophyll content) levels result in higher reflectance and higher subsequent NDVI values and a high R^2 with plant N concentration.

Sensor Movement Speed and Wind:

Amber Sensor:

Sensor movement over the canopy as well as wind variables were tested to determine if these variables affected the ability of active sensors to differentiate N status of the plant (Table 2.4, Figure 2.5a). No comparison of sensor speed or wind on NDVI could be found in the literature; however other studies show that external variables such as sensor position (Hodgen et al., 2004) or leaf wetness (Solari et al., 2004) rarely affect the NDVI of active sensors due to the frequency of the readings. Results show that there were no significant differences in the NDVI readings with or without wind. Both the red and amber sensors recorded the same NDVI values regardless of the wind speed and subsequent leaf movement. Therefore, the wind variable was removed from this discussion.

Results for sensor movement speed show that the amber sensor recorded no significant differences across movement speed (Table 2.4, Figure 2.5a) indicating the amber sensor was not affected by movement. The frequency of measurements recorded by the amber sensor is great enough to negate any affects of sensor movement.

Red Sensor:

Sensor movement speed had a significant affect on the NDVI readings of the red sensor (Table 2.4, Figure 2.5b). The red sensor showed significantly lower NDVI readings when moved at 3.6 km hr^{-1} across the top of the canopy when compared to 0.72 km hr^{-1} and stationary (0.0 km hr^{-1}). By moving more rapidly over the top of the canopy the red sensor was not able to record as high of a reflectance value meaning less light was returning to the sensor due to its movement. The red sensor has 1 detector recording both NIR reflectance and the visible light reflectance. To accomplish this, the red sensor must oscillate between each reading. This effectively cuts in half the number of NDVI readings as both the NIR and visible measurements are needed for this calculation. Our results show that the red sensor speed over the crop canopy can affect readings making consistent use very important. This is in contrast to the amber sensor which showed no significant differences in sensor movement speed allowing for a greater variation in speed across a field. The amber sensor has two detectors, one each for NIR and the visible band allowing for more and faster NDVI calculations. Overall this should not be an issue with the red sensor assuming the user can maintain a constant speed through the field.

CONCLUSIONS

Nitrogen application rate and maize growth stage affected the NDVI readings of both sensors with the NDVI values generally increasing with increased N application rate and advancing maize growth stage. This also demonstrates the principles by which these sensors operate. As LAI and maize leaf greenness increase (narrower row spacing and increased N and maize growth stage) light reflectance increases and so does the NDVI value.

The amber sensor was not affected by maize row spacing at the V10 and V12 maize growth stages maintaining R^2 values in the mid to high eighties across all widths tested. The V8 R^2 values for both sensors were lower than those at the V10 and V12 growth stages suggesting that these sensors are most accurate and best used at the V10 to V12 maize growth stage after differences in maize growth (LAI) have had time to develop. While the amber and red sensor performed equally for the most part, the variability in the red sensor suggests that the amber sensor may be more reliable under the conditions tested.

Sensor speed also had an affect on red sensor NDVI values. When the red sensor was moved rapidly over the canopy NDVI values decreased compared to slow and stationary movement NDVI. The amber sensor was not affected by sensor movement displaying almost identical NDVI values regardless of movement speed over the maize canopy. This suggests that consistency of operation is more important with the red NDVI unit than with the amber sensor.

We found that both the amber and red sensors distinguish differences in the plant N status and growth stage differences in maize in a greenhouse environment and each had high R^2 values with applied N rate and plant N concentration. However, the red sensor had more variability in NDVI readings and it does require more attention due to the affect of movement. The amber sensor shows no such limitations and therefore performed best under greenhouse conditions. It is logical to assume that similar results would be obtained under field conditions.

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Table 2.1. Amber NDVI readings in maize across 4 N rates, 3 row spacing widths and 3 growth stages under greenhouse conditions.

	Nitrogen Rate (kg ha^{-1})				
	0	75	150	225	
	---------------------Amber NDVI---------------------				
Nitrogen Rate Average	0.369	0.501	0.551	0.598	
Row Spacing		**V8**			**Average**
25 cm	0.457	0.467	0.518	0.582	0.506
50 cm	0.333	0.342	0.352	0.422	0.362
75 cm	0.296	0.323	0.334	0.424	0.344
		V10			
25 cm	0.451	0.610	0.667	0.665	0.598
50 cm	0.360	0.463	0.545	0.603	0.493
75 cm	0.354	0.451	0.527	0.570	0.476
		V12			
25 cm	0.447	0.676	0.722	0.730	0.644
50 cm	0.370	0.620	0.692	0.687	0.592
75 cm	0.342	0.606	0.670	0.679	0.574
Row Spacing					**Average**
25 cm	0.452	0.585	0.636	0.659	0.583
50 cm	0.354	0.475	0.530	0.571	0.482
75 cm	0.331	0.460	0.510	0.558	0.465
Growth Stage					**Average**
V8	0.362	0.377	0.401	0.476	0.404
V10	0.389	0.508	0.580	0.613	0.522
V12	0.386	0.634	0.695	0.699	0.603
Analysis of Variance	***P* > *F***	**($LSD_{0.05}$)**			
Nitrogen Rate (NR)	<0.0001	0.006			
Growth Stage (GS)	<0.0001	0.007			
NR x GS	<0.0001	0.013			
Row Spacing (RS)	<0.0001	0.006			
NR x RS	0.0009	0.011			
GS x RS	<0.0001	0.012			
NR x GS x RS	<0.0001	0.022			

Table 2.2. Red NDVI readings in maize across 4 N rates, 3 row spacing widths and 3 growth stages under greenhouse conditions.

	Nitrogen Rate (kg ha^{-1})				
	0	75	150	225	
	Red NDVI				
Nitrogen Rate Average	0.446	0.609	0.686	0.733	
Row Spacing		**V8**			**Average**
25 cm	0.562	0.547	0.601	0.707	0.604
50 cm	0.387	0.354	0.443	0.505	0.422
75 cm	0.351	0.364	0.390	0.538	0.411
		V10			
25 cm	0.529	0.721	0.817	0.764	0.708
50 cm	0.410	0.521	0.749	0.691	0.593
75 cm	0.380	0.558	0.703	0.666	0.577
		V12			
25 cm	0.561	0.845	0.918	0.914	0.810
50 cm	0.476	0.821	0.896	0.886	0.770
75 cm	0.437	0.807	0.886	0.845	0.744
Row Spacing					**Average**
25 cm	0.550	0.704	0.779	0.795	0.707
50 cm	0.424	0.565	0.696	0.694	0.595
75 cm	0.389	0.577	0.660	0.683	0.577
Growth Stage					**Average**
V8	0.433	0.422	0.478	0.583	0.479
V10	0.439	0.600	0.756	0.707	0.626
V12	0.491	0.824	0.900	0.882	0.774
Analysis of Variance	***P* > *F***	**($LSD_{0.05}$)**			
Nitrogen Rate (NR)	<0.0001	0.020			
Growth Stage (GS)	<0.0001	0.022			
NR x GS	<0.0001	0.040			
Row Spacing (RS)	<0.0001	0.017			
NR x RS	<0.0004	0.003			
GS x RS	0.0217	0.073			
NR x GS x RS	0.0083	0.034			

Table 2.3. Maize total plant and leaf N concentration at the V12 growth stage under greenhouse conditions.

N Rate (kg ha^{-1})	Total Plant N Concentration	Corn Flag Leaf N Concentration
	----------------mg kg^{-1}---------------	------------------mg kg^{-1}-----------------
0	0.93	0.94
75	1.33	1.46
150	1.65	1.70
225	1.65	1.85
P>F	0.0073	0.0100
$LSD_{(0.05)}$	0.41	0.37

Table 2.4. Amber and red NDVI readings in maize across fast, slow and stationary sensor movement speeds under greenhouse conditions.

Sensor Movement	Amber NDVI	Red NDVI
Fast	0.505	0.590
Slow	0.503	0.639
Stationary	0.506	0.627
P>F	0.6024	<0.0001
$LSD_{(0.05)}$	-----	0.016

Figure 2.1a. Maize amber NDVI as affected by applied N rate at 25 cm row spacing at the V8, V10 and V12 growth stage under greenhouse conditions.

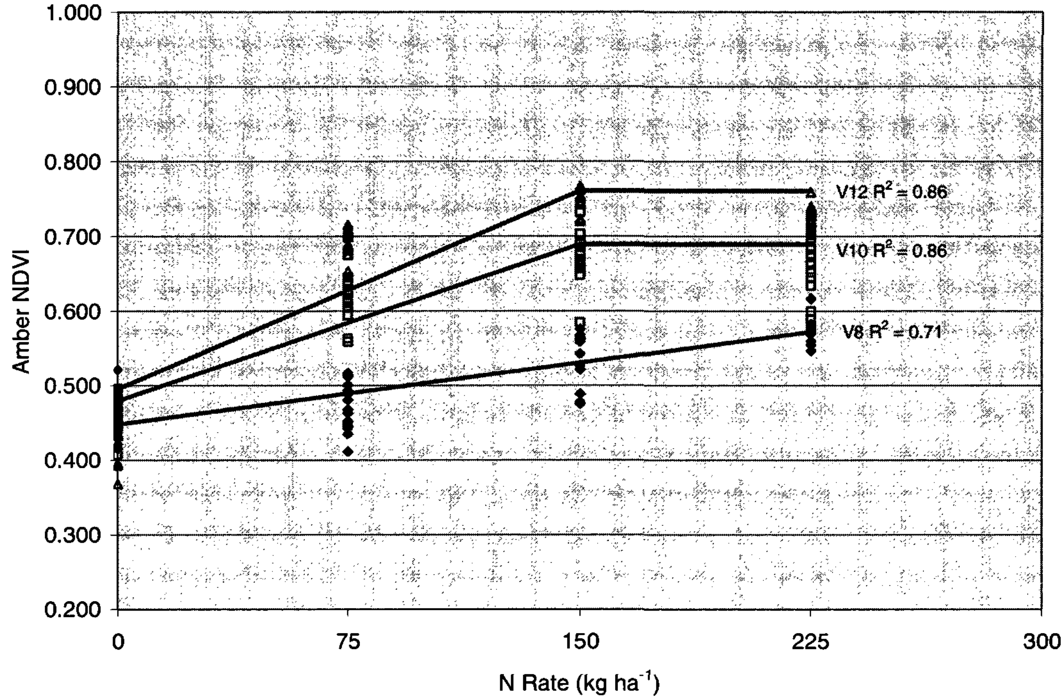


Figure 2.1b. Maize red NDVI as affected by applied N rate at 25 cm row spacing at the V8, V10 and V12 growth stage under greenhouse conditions.

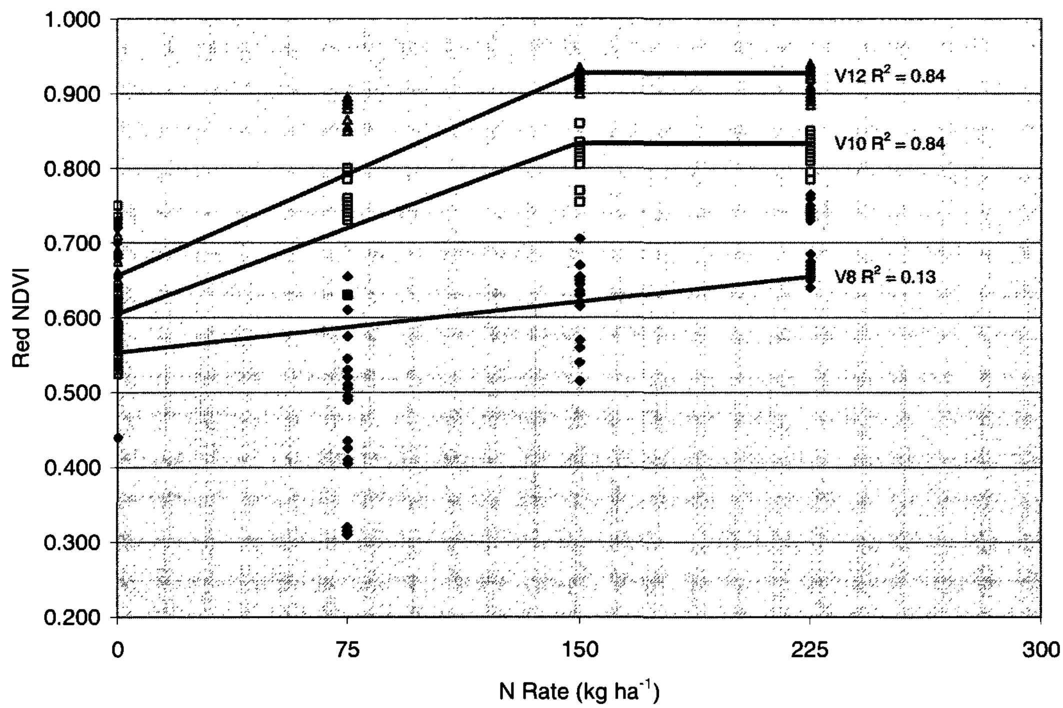


Figure 2.2a. Maize amber NDVI as affected by applied N rate at 50 cm row spacing at the V8, V10 and V12 growth stage under greenhouse conditions.

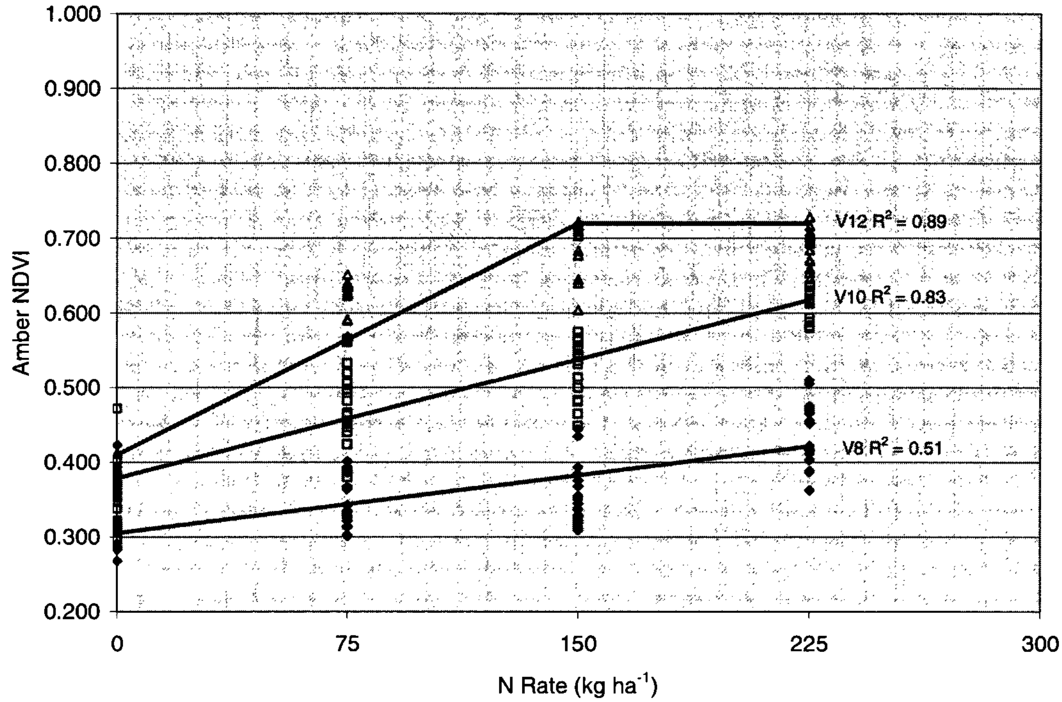


Figure 2.2b. Maize red NDVI as affected by applied N rate at 50 cm row spacing at the V8, V10 and V12 growth stage under greenhouse conditions.

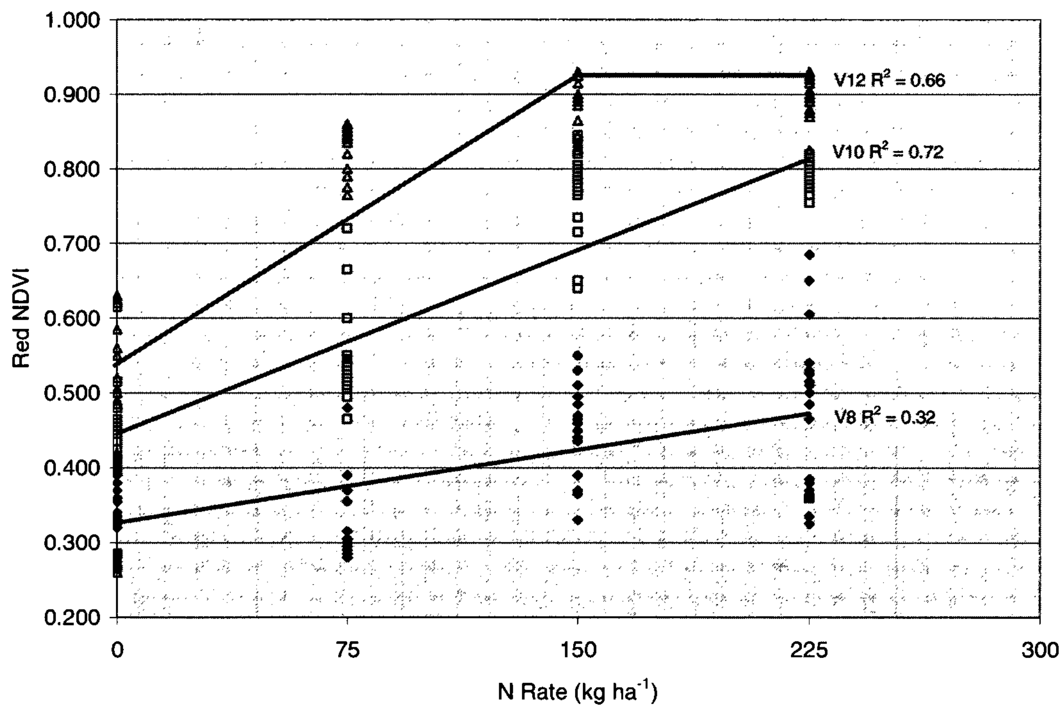


Figure 2.3a. Maize amber NDVI as affected by applied N rate at 75 cm row spacing at the V8, V10 and V12 growth stage under greenhouse conditions.

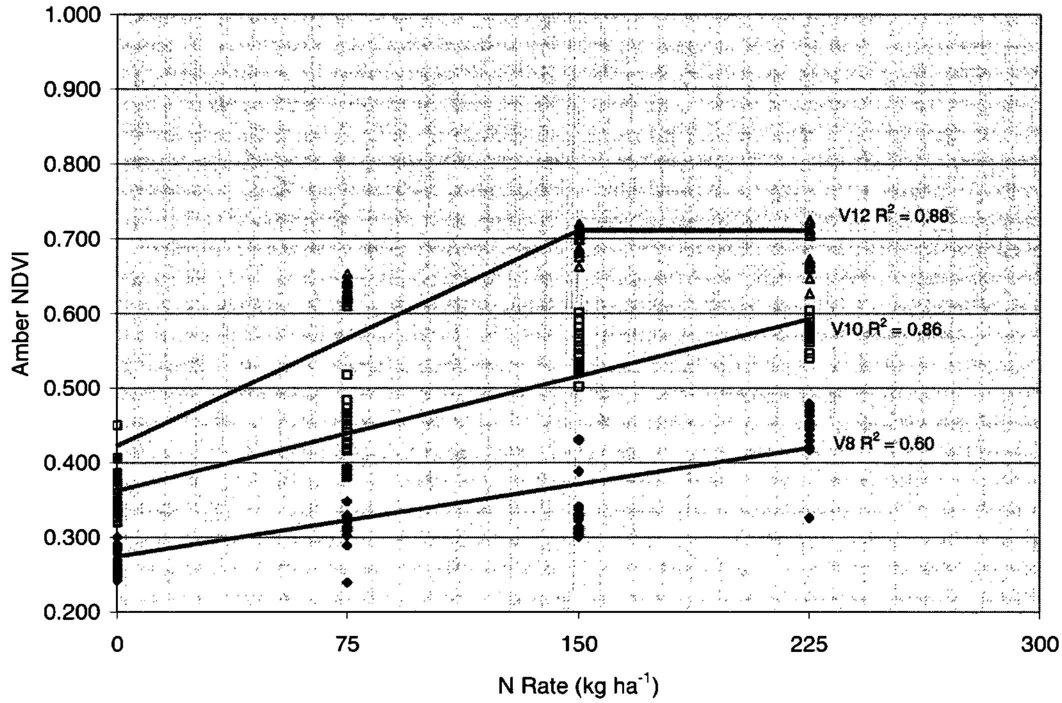


Figure 2.3b. Maize red NDVI as affected by applied N rate at 75 cm row spacing at the V8, V10 and V12 growth stage under greenhouse conditions.

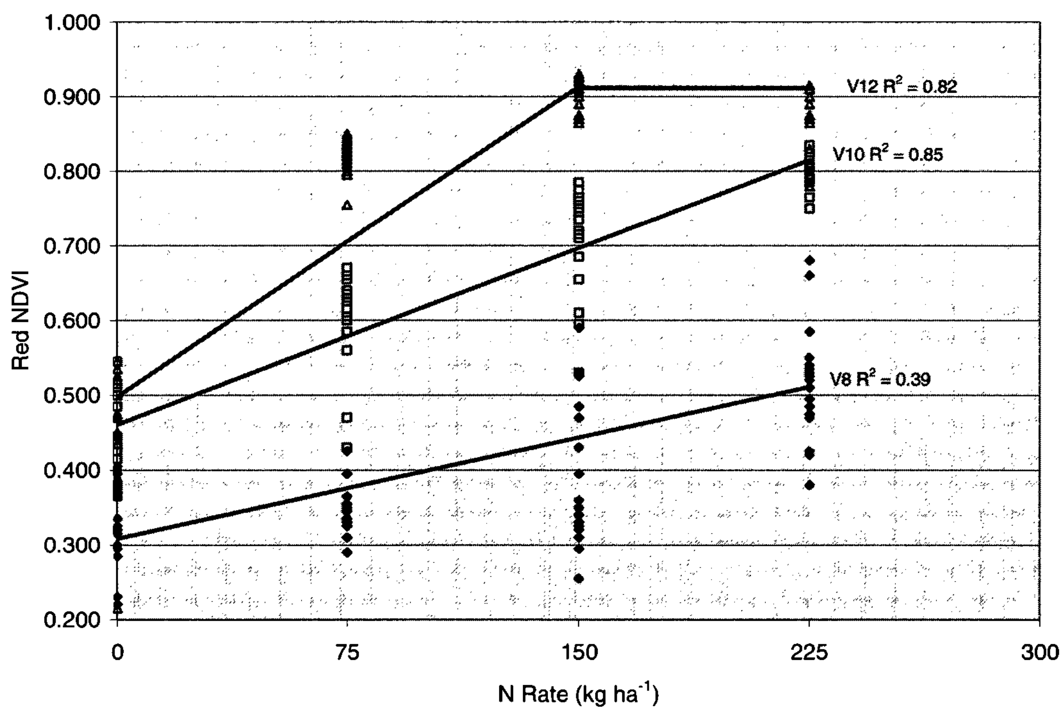


Figure 2.4a. Maize amber NDVI as affected by maize total plant and leaf N concentration under greenhouse conditions.

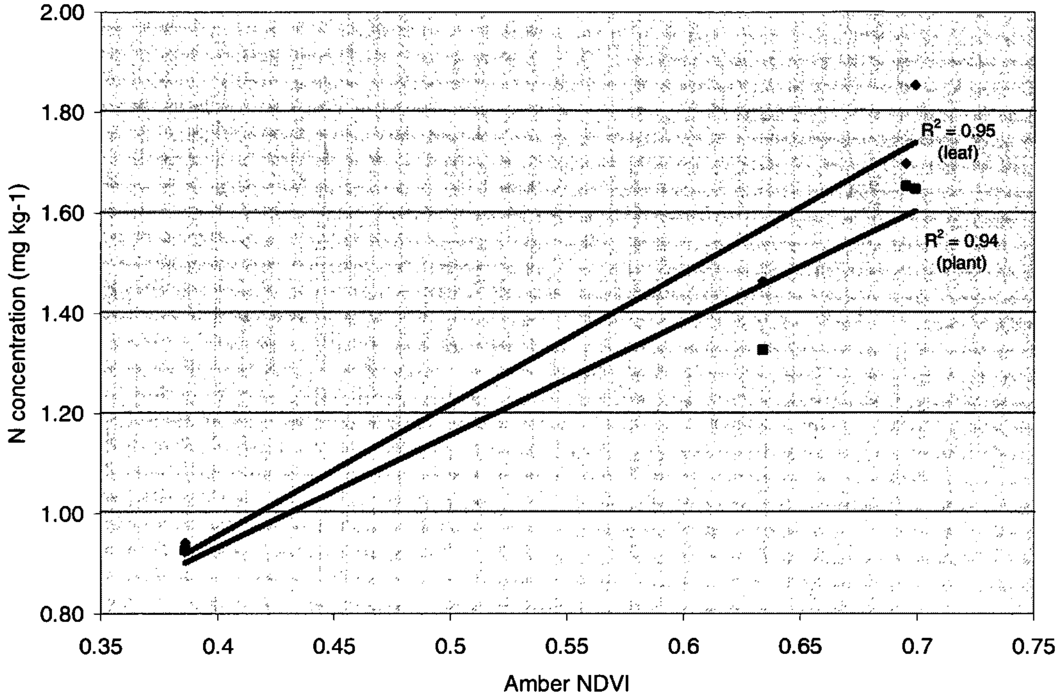


Figure 2.4b. Maize red NDVI as affected by maize total plant and leaf N concentration under greenhouse conditions.

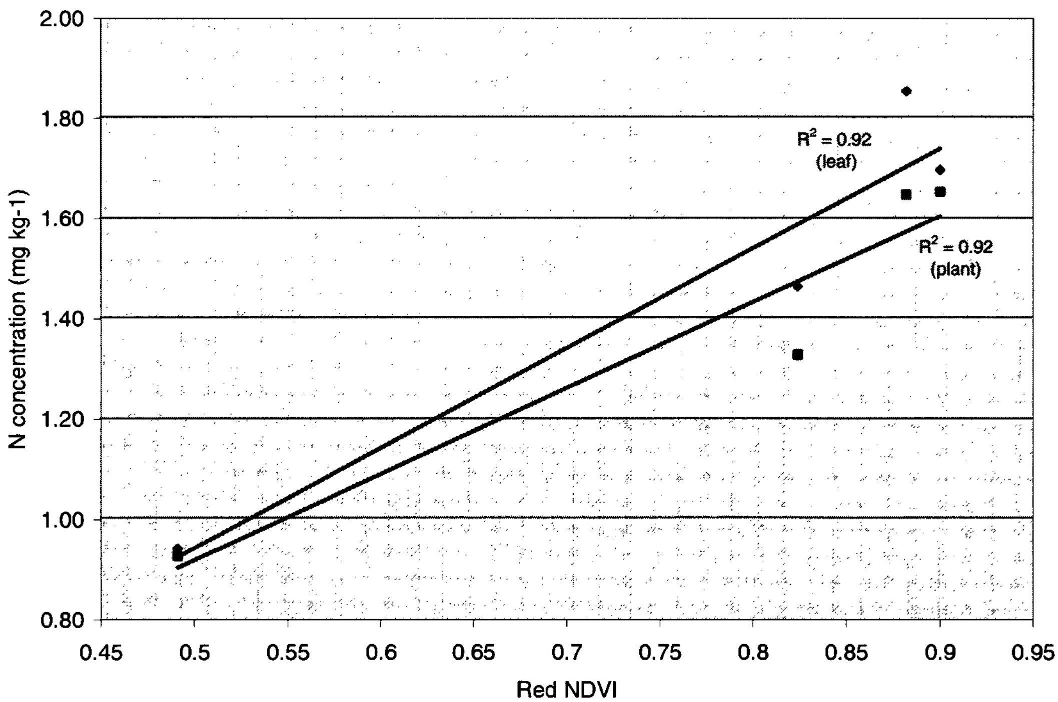


Figure 2.5a. Maize amber NDVI readings across fast, slow and stationary sensor movement speeds under greenhouse conditions.

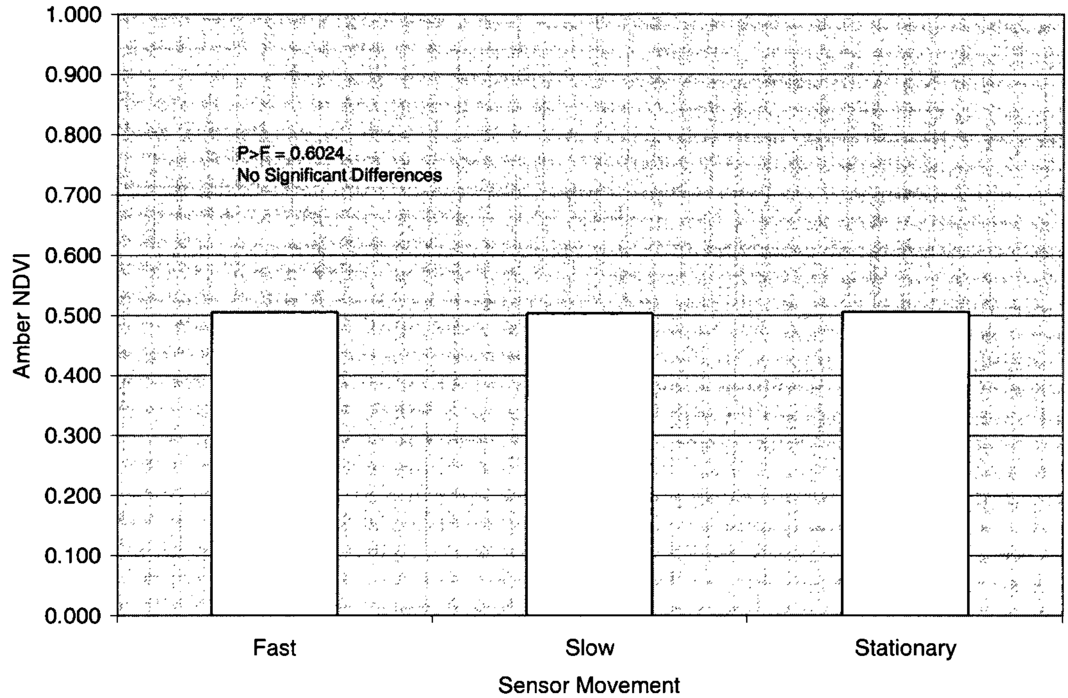
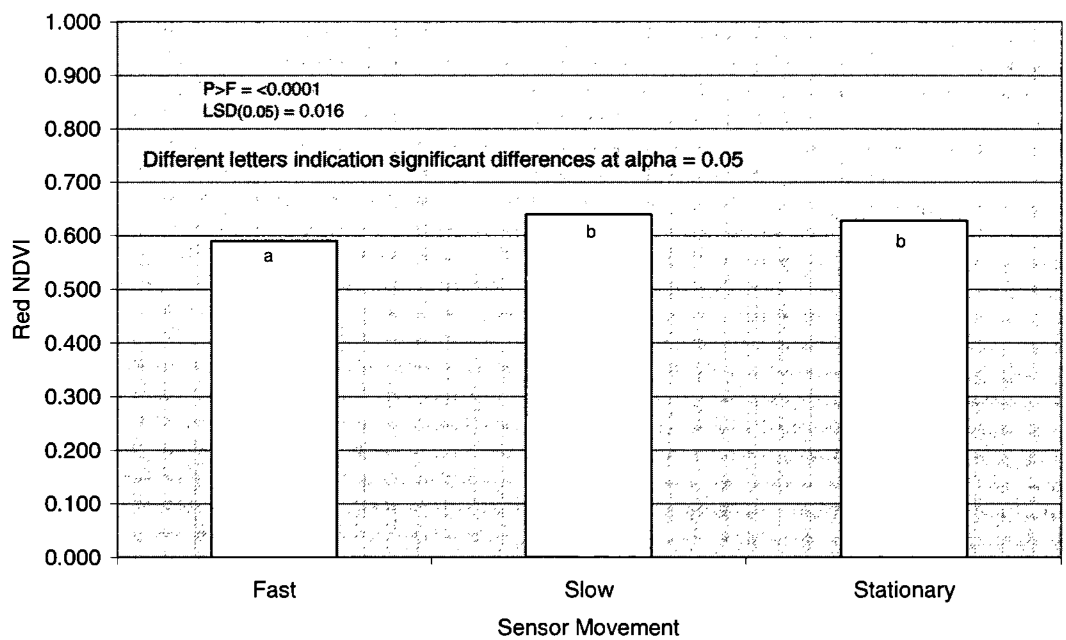


Figure 2.5b. Maize red NDVI readings across fast, slow and stationary sensor movement speeds under greenhouse conditions.



CHAPTER 3

Evaluation of ground-based active remote sensors for nitrogen management in irrigated maize

ABSTRACT

Recent advances in precision agriculture technology have led to the development of ground-based active remote sensors that determine normalized difference vegetation index (NDVI). Studies have shown that NDVI from active sensors is highly related with leaf N content as well as N and water stress in maize (*Zea mays*). Remotely sensed NDVI imagery can provide valuable information about in-field N variability in maize and significant linear relationships between sensor NDVI and maize grain yield have been found suggesting that an N recommendation algorithm based on NDVI could optimize N application. Therefore, a study was conducted to determine the performance of the two most prominent active sensors (NTech's GreenSeeker™ red and Holland Scientific's Crop Circle™ amber) by studying their relationships with applied N rate and grain yield. We also wanted to determine if ancillary variables such as soil NO_3 concentration, leaf N concentration, SPAD chlorophyll and plant height used in conjunction with NDVI could increase sensor effectiveness. The 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 ancillary variables

substantially increased the R^2 over using NDVI alone. Therefore, an N recommendation algorithm was developed for use at the V12 maize growth stage for both the amber and red sensors using only NDVI. These algorithms calculated very similar N recommendations, again suggesting that the amber and red sensors perform equally. Also, each sensor NDVI N recommendation algorithm calculated unbiased N recommendations suggesting that each was a valid estimator of required N at maize growth stage V12 to achieve optimum grain yield. The amber and red sensors both perform very well in the determination of N variability in irrigated maize at the V12 and V14 growth stage and the integration of these sensors and the appropriate N application algorithms into an on-the-go fertilizer application system would increase the spatial accuracy of N application on fields that are spatially variable if these algorithms are shown to be stable over time and space.

INTRODUCTION

Recent advances in precision agriculture technology have led to the development of ground-based active remote sensors (or active 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 this index. Active sensors allow for the determination of NDVI at specific times and locations throughout the growing season without the need for ambient illumination or flight concerns. These sensors are referred to as "active" indicating the sensors have their own light source instead of relying on ambient light needed for airborne or satellite sensors which are labeled as "passive" sensors. Active sensors are relatively small in size and operate by directing sensor produced visible light (VIS) as well as near infrared (NIR) light at the plant canopy of interest. The amount of VIS and NIR light that is reflected off of the plant canopy is collected by the active sensor and a NDVI value is calculated using Equation 1.

$$NDVI = (NIR - VIS) / (NIR + VIS) \quad \text{[Eq. 1]}$$

where: NIR = near infrared and VIS = visible light wavelength

The visible light (400-720nm) reflectance is primarily dependant on the chlorophyll contained in the palisade layer of the leaf (Campbell, 2002) 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 maize (*Zea mays*) 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 relate with 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 showing N deficiency.

Studies have shown that leaf reflectance has a good relationship with leaf N content (Alchanatis et al., 2005; Osborne et al., 2002; Bausch et al., 1998; Bausch and Duke, 1996; Schepers et al., 1996; Blackmer, 1994) as well as N and water stress in maize (Clay et al., 2006; Osborne et al., 2004). Other studies have been conducted verifying that remotely sensed NDVI imagery can provide valuable information about in-field N variability in maize (Shanahan et al, 2001; Scharf and Lory, 2002; Chang et al, 2003; Sripada et al., 2005). High linear relationships between sensor NDVI and maize grain yield have also been found (Chang et al., 2003; Osborne et al., 2002; Baez-Gonzalez et al., 2002; Shanahan et al., 2001).

Studies specific to active sensors have shown that NDVI readings adequately quantify maize variability (Raun et al., 2005) and relate well with many variables that affect maize yield as well as the yields themselves. Martin et al. (2007) found that NDVI increased with maize growth stage during the crops life cycle and a linear relationship with grain yield was best at the V7 to V9 maize growth stages. 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 V8 to V10 maize growth stage NDVI x plant height with by-plant forage yield on an area basis and suggested that this index may be used to refine midseason fertilizer N rates based on expected N removal at or before V10. Substantial linear relationships have also be shown between NDVI and maize forage and grain yields when NDVI readings are collected between the growth stage development window of V5 to V9 (Thomason et al., 2007). Similar results were found by Teal et al., (2006) with NDVI and grain yield relations between the V7 to V9 growth stages. Inman et al. (2007) found that a sensor produced NDVI-ratio calculated from the reflectance of the area of interest and the reflectance from an N-rich portion of the same field had a significant relationship with observed maize grain yield. The authors suggested that this sensor has the potential to estimate maize grain yield, however improvements need to be made.

The aforementioned studies illustrate the relationship between NDVI and maize crop variables that affect maize yield. There are also several studies that have been conducted in wheat (*Triticum aestivum*) that demonstrate similar relationships. Research conducted by Girma et al., (2006) found that multiple-linear regression analysis of mid-season NDVI readings, chlorophyll content, plant height, and total N uptake were good predictors of winter wheat yields. Work by Raun et al., (2002) has shown that the use of a response index (RI) can be used to estimate N application rates based on yield predictions in winter wheat. This RI uses the NDVI readings of an N-rich (reference) portion of the field divided by the NDVI readings of a target area of the field to give a normalized response index that can then be used in conjunction with other variables to determine an N recommendation. The RI equation is presented below as Equation 2.

$$RI = NDVI_{Reference} / NDVI_{Target} \qquad \text{[Eq. 2]}$$

where: $NDVI_{Reference}$ = NDVI of N-Rich Plot

$NDVI_{Target}$ = NDVI of Managed Plot

Using the RI method an increase in N use efficiency (NUE) of more than 15% was observed over conventional N application methods. Lukina et al., (2001) has shown that the integration of active sensor based N fertilizer algorithms based on predicted yield can greatly increase NUE in wheat and Apacaricio et al., (2002 and 2000) found that NDVI accurately tracked changes in wheat leaf area index (LAI) when data were analyzed across a broad range of different growth stages, environments and genotypes and that the usefulness of NDVI and simple ratio for calculating green area and grain yield is limited to LAI values < 3 (Range 0 -6).

Obviously a substantial amount of testing of active sensors has been conducted, and they perform very well. However, active sensors had not been tested in Colorado and a study was warranted to determine how the two most prominent commercially available active sensors (NTech's GreenSeeker™ and Holland Scientific's Crop Cricle™) would perform under our climatic conditions and management practices. These sensors each operate under the same set of scientific principles. A detailed description of the GreenSeeker™ sensor operation is available in Inman et al. (2005). Essentially, the two sensors evaluated operate using different wavelengths of visible light (VIS) used for canopy reflectance and NDVI determination. The GreenSeeker™ sensor uses a red visible light (hereby referred to as: red sensor) and the Crop Circle™ uses an amber visible light (hereby referred to as: amber sensor). Although these sensors operate similarly it is quite possible that one sensor may perform the task of NDVI determination better than the other. This could be due to engineering or simply that one wavelength performs better when used in maize than the other.

Researchers are developing active sensor based algorithms for N recommendations in maize. Generally the algorithms are specific to either the amber or red sensor. One exception to this is the algorithm developed by Kitchen (2006) who has developed specific algorithms for both the amber and red sensors. These algorithms are based on sensor readings from a reference (N-rich) area of the field and a target (to be applied) area of the field. The algorithms determine the N recommendation by dividing the simple ratio (SR) of the target area by the simple ratio of the reference area to create a RI based on plant response. The equation for SR is presented as Equation 3:

$$SR = VIS / NIR \qquad \text{[Eq. 3]}$$

where: VIS = Visible light eeflectance and NIR = Near infrared light reflectance

By performing this calculation the data is normalized or brought to a similar scale that can be compared. The wider the discrepancy in reflectance values from the reference and target areas the larger the RI resulting in a higher N recommendation based on the RI's relationship with grain yield, plant N or other factors that relate to plant growth. Essentially the RI indicates the difference in maize growth from a well fertilized area of the field and a non-fertilized area of the field and the algorithm estimates the amount of N needed to make up this difference.

The NDVI RI concept is also used in other N recommendation algorithms. Nitrogen recommendation algorithms for wheat (Lukina et al., 2001), maize (Tubana et al., 2008) and cereal crops (Raun et al., 2005) have been developed for the red sensor at that are based in some part on plant NDVI response to applied N. The maize algorithm (Tubana et al., 2008) uses the same RI concept. However, in this case the index is the NDVI of the reference strip is divided by the NDVI of the target area of the field. This value is then plugged into an equation that uses expected N use efficiency (NUE), grain N content, maximum, critical and plot coefficient of variation of recorded NDVI and also predicts in-season estimated yield (INSEY) from Teal et al. (2006). This algorithm is very elaborate and uses a great deal of information to give an N recommendation. Work by this group has also shown that using optical sensors and variable rate applications of N can increase NUE by more than 15% over conventional N application methods.

Solari et al. (2008) also has developed sensor based N estimation algorithms using the RI concept. However, they call it the sufficiency index (SI); it is the target area sensor readings divided by the reference area readings. The SI is based on chlorophyll meter readings and was developed by Varvel et al. (2007) along with an N recommendation algorithm based on SI. This algorithm was then adapted for use with amber sensor and with a chlorophyll index (NIR / VIS $_{590(\text{amber})}$) by Solari et al. (2008)

who found that the chlorophyll index was best suited to direct variable N applications using the adapted algorithm when compared to amber sensor or chlorophyll meters.

Whatever the difference in methodology when devising an N recommendation algorithm the overriding principle guiding the algorithm in previous studies is a normalized RI of an N-rich area and a target or managed area. This concept allows for direct comparisons to be made and is proven to have a high linear relation with N application levels and grain yield.

Since development of an N recommendation algorithm is our overall goal, we determined that our first course of action should be establishment of which sensor, amber or red, performed best in our region. We also wanted to determine at which maize growth stage each sensor performed best and if ancillary variables that are related to maize growth could be used in conjunction with NDVI to increase the effectiveness of each sensor. These variables included soil NO_3 concentration (0-20 cm depth), flag leaf total N concentration, SPAD leaf chlorophyll content, and plant height. Each variable is known to affect overall maize growth, and when used in conjunction with NDVI, could increase sensor relationships with grain yield. We thought that this relationship could be improved because we are increasing the number of parameters measured, thereby increasing our measurement of crop variability. Finally, after determining the optimum conditions for sensor use, an N recommendation algorithm could be developed using the RI concept that previous studies have established.

Our objectives were: (1) To determine the effectiveness of two commercially available active sensors across several maize growth stages and N application rates. (2) To determine if ancillary soil and crop variables known to affect maize growth and yield can be used in conjunction with NDVI to increase sensor relationships with grain yield. (3) To develop an in-season N recommendation algorithm based on NDVI calculated from active sensors.

MATERIALS AND METHODS

Study Sites:

This study was conducted at Colorado State University's Agricultural Research Development and Education Center (ARDEC) located near Fort Collins, Colorado (latitude 40° 40' 38.24" N, longitude 104° 59' 44.76" W) and in summer 2006. The field site used was furrow irrigated continuous maize and was classified as a fine-loamy, mixed, superactive, mesic, Aridic Haplustalf (Soil Survey Staff, 1980). Two different locations within the same field were used for this study resulting in two site years.

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 unit manufactured by NTech Industries Inc. 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 sensor produced visible light as well as near infrared (NIR) light (770nm) at the plant canopy of interest. The amount of visible and NIR light that is reflected off of the plant canopy is collected and a normalized difference vegetation index (NDVI) value is calculated. The NDVI equation is presented above as Equation 1. 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 red GreenSeeker™ generates a red light (wavelength 660nm) in the visible spectrum. Therefore, the NDVI value calculated by the red GreenSeeker™ will be referred to as "Red NDVI".

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

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 telescoping boom allowing readings to be collected at all maize growth stages of interest. The red sensor was held 100 cm above the maize canopy. This is in the middle of the range (80-120 cm) suggested by the manufacturer's instruction manual (NTech Industries, Inc., 2005). The amber sensor was held 70 cm above the maize canopy as readings were collected. This was the middle of the manufacturers range (50-90 cm) for this sensor (Holland Sci., 2005). The red sensor was connected to a Compaq Ipaq™ hand-held computer to record NDVI values. The amber sensor was connected to Holland Scientific's GeoSCOUT GLS-400 data logger (Holland Sci., 2006) to record all 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 maize plants most mature leaf for total N content, maize 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 Harris Labs in Lincoln, NE..

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 0-20 cm. 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 Harris Labs in Lincoln, NE.

SPAD chlorophyll content readings were collected within each N application rate plot. Readings were collected from five random most mature leaves in each plot. 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.

Nitrogen Application and Plot Design:

Nitrogen was applied as 32-0-0 urea-ammonium-nitrate (UAN) at maize emergence (no pre-plant N was applied) using a 4-row side-dress applicator with variable rate capabilities. This applicator applied liquid N below and to the side of the maize plant. The N was applied as close to a scheduled irrigation event as possible to reduce potential N losses due to volatilization. Four N rates were applied; 0, 50, 100, and 175 kg N ha^{-1}. Sub-plots of each N application rate were set up at two different locations (site years 1 and 2) at ARDEC and each N rate was replicated four times at each site year in a complete randomized block (CRB) design. This resulted in 16 sub-plots within each site year. Each plot was 4 maize rows in width (76 cm row spacing) and 15 meters long. Site years 1 and 2 had not received applied N for two years prior to this study.

Maize Grain Yield:

Maize grain yield was determined by harvesting with a two-row Massey Ferguson plot combine equipped with a Harvest Master HM-401 CCU yield monitor. This yield monitor recorded grain weight over distance traveled. Sub-samples of maize grain from each plot also were also collected with the combine. The moisture and test weight were then determined from the sub-sample using a Dickey-john® GAC model 2100 grain analysis computer. The grain weight was adjusted to 15.5% moisture and scaled to a Mg ha^{-1} yield basis.

NDVI Based Nitrogen Algorithm Development:

Our NDVI based N estimation algorithms for the amber and red sensors were created by using the maize growth stage V12 NDVI readings from the 0, 50, 100 and 175 kg ha^{-1} N plots in site-years 1 and 2. This algorithm was created at the V12 growth stage because maximum N variability was recorded by the active sensors at the V12 growth stage (see results section) and the maize is still small enough to allow N application implements into the field. To create the algorithms in this paper a wide range of NDVI RI's were created by dividing the NDVI of an N applied plot by the NDVI of a 0 kg ha^{-1} plot. This RI will be referred to as the $RI_{Algorithm}$ as it was used to create the algorithms and is different from the RI presented in Equation 2 which is used in the algorithms to estimate crop N need. The $RI_{Algorithm}$ equation is presented as Equation 4.

$$RI_{Algorithm} = NDVI_{N\ plot} / NDVI_{0\ N\ plot} \qquad \text{[Eq. 4]}$$

where: $NDVI_{N\ plot}$ = NDVI readings from N applied plots (50, 100 and 175 kg ha^{-1})

$NDVI_{0\ N\ plot}$ = NDVI readings from 0 kg ha^{-1} plot

The calculated $RI_{Algorithm}$ values were then plotted against the N application rate difference that created that RI (50, 100 or 175 kg ha^{-1}). The overall idea with this algorithm is that a RI can be based on N application differences. If we know the difference in N application rates and the resulting RI this information can be plotted and an N prediction equation can be formulated through linear regression. This process was repeated for all possible $RI_{Algorithm}$ values across 50, 100, and 175 kg ha^{-1} N application rates. An RI of 1.0 was used at the 0 kg ha^{-1} N application rate assuming that if the $NDVI_{Reference}$ was divided by the $NDVI_{Target}$ (Equation 2) and a RI of 1.0 was recorded no additional N would be needed because the target area and reference area would have the same N status.

The $RI_{Algorithm}$ values were then regressed on applied N using polynomial regression and an N recommendation prediction equation was formulated. The intercept for the regression equation was set at 1.0 because this is the lower limit of the RI (at 1.0 no N is needed).

Algorithm Validation:

After algorithm development validation was required. However, one limitation was that we only had our own data set upon which a validation test could be performed. Therefore, a test for N prediction bias was performed. This test was conducted by using the NDVI data collected from site-years 1 and 2 across 4 N rates applied at maize emergence (0, 50, 100 and 175 kg ha^{-1}) (using the NDVI readings from the 175 kg ha^{-1} N applied plots as the reference data) to create N recommendations at the V12 maize growth stage. This created varying supplemental N recommendations as each plot had different amounts of N applied at maize emergence. Next a 95% confidence interval was calculated for each algorithm N recommendation. Finally 100 "bootstrapped" (with replacement) random samples were created for each N application plot. This bootstrapping process created 100 random NDVI data sets (for each N plot) from the original NDVI data. Sampling with replacement allowed duplicate samples to be used in the randomization so that the original number of samples was kept constant allowing for comparisons across the same sample population number. This process was conducted for both the amber and red NDVI algorithms. The bootstrapped N recommendations were then compared to the actual N recommendation 95% confidence interval to determine what percentage of the bootstrapped samples fit within this margin. If the algorithms are unbiased we would expect to see approximately 95% of the random bootstrapped samples fit in the 95% confidence interval.

Data Analysis:

All statistical analysis was performed using the Statistical Analysis System (SAS) (SAS Institute, 2006). All regressions and 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. The bootstrapping process was done using a bootstrapping macro in SAS. Proc MEANS was used for all means calculations and the CLM option was used in Proc MEANS for all confidence interval calculations.

RESULTS AND DISCUSSION

Maize Grain Yield:

Grain yield was significantly increased by applied N fertilizer in both site years (Tables 3.1 and 3.2, Figures 3.1 and 3.2). Yields were highest 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. All applied N rates yielded significantly more than the check (0 kg ha^{-1}). Yields in site-year 2 were similar to those in site-year 1, and again the 175 and 100 kg ha^{-1} N rates produced the same yield. This again suggests that the N sufficiency level was reached at the 100 kg ha^{-1} rate.

The observed yield differences due to N application indicate that there are sufficient differences in maize growth in both site-years 1 and 2 to adequately test the active sensors. The amber and red sensors should be able to distinguish applied N rates based on biomass and N concentration differences within the maize plants. The treatments that yielded highest should have greater NDVI values and vice versa as greater plant biomass and N content are directly related to applied N and directly affect maize grain yield. If a sensor is performing properly we would expect NDVI readings to 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. This is primarily because during both site-years, N sufficiency was reached at the 100 kg ha^{-1} N rate. No significant increase in grain yield was observed above the 100 kg ha^{-1} N rate meaning the NDVI readings should also plateau at this level. Consequently, a segmented regression (linear plateau model) was used to describe NDVI readings.

Sensor Comparison:

Site-Year 1 NDVI:

Site-year 1 NDVI readings across N application rates and V8, V10, V12 and V14 maize growth stages are shown for both the amber (Table 3.2, Figure 3.3) and red (Table 3.3, Figure 3.4) sensors. The amber and red sensor results were the function of a 2-way applied N rate x maize growth stage interaction for both site-year 1 and site-year 2. However, it was determined that linear relations 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 maize growth stages. The primary difference between the amber and red sensors are the range in which the NDVI is reported. The amber sensor's NDVI range was approximately 0.270 to 0.700, whereas the red sensor had a wider range of NDVI readings from approximately 0.250 to 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 sensor electronics and did not affect linear relationships. It does suggest, however, that the red sensor could reach saturation earlier in the growing season than the amber unit. As the maize crop matures the NDVI values should increase and our results show that higher NDVI values were recorded with the red sensor at the same growth stage than with the amber sensor. Therefore, the red sensor will reach a maximum (saturate) earlier in the growing season than the amber sensor.

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 reach a plateau across the 50, 100 and 175 kg ha^{-1} rates. 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. The NDVI levels were not significantly different across the 50, 100 and 175 kg ha^{-1} N rates for either the amber or red sensor. Therefore, a linear-plateau regression was performed. High linear relations between NDVI and N rate were observed for both sensors with the amber sensor having an R^2 of 0.89 and the red sensor an R^2 of 0.82. This model also has been used when NDVI plateaus across maize LAI, maize forage yield (Thomason et al., 2007) and when maize grain yield plateaus across applied N rate (Dellinger et al., 2008; Varvel et al., 2007).

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. Similar results were reported by Freeman et al. (2007) who showed an increase in NDVI with increased maize N uptake.

NDVI values also increased across maize growth stage. This also has been reported in studies by Martin et al. (2007) and Raun et al. (2004) who showed increasing NDVI with maize growth stage until tassel (VT) when NDVI then decreased. 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 will increase with growth stage.

As discussed previously, there were no yield differences between the 100 and 175 kg ha^{-1} treatments (Table 3.1, Figure 3.1), indicating there was little difference in plant growth leading to the similarities in NDVI readings at these N application levels. Using segmented regression across the 100 and 175 kg ha^{-1} N rates high liner relationships were again found between NDVI and N rate at each maize growth stage with each sensor. Linear relationships for each sensor at the V14 growth stage showed the amber sensor having an R^2 of 0.92 and the red sensor having an R^2 of 0.89. Similar R^2 values were observed at the V12 maize growth stage values of 0.90 and 0.87 for the amber and red sensors, respectively, suggesting that these sensors perform best at the V12 to V14 range. Studies based in other regions of the U.S. suggest that earlier growth stages (V6 or V8 to V10) are the optimum times to take NDVI readings (Kitchen 2006; Raun et al., 2005 and 2002) based on timing related to maize N variability expression. Maize N variability expression appears to occur later in the growing season in Colorado than in mid-western areas of the U.S. 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 (Solari et al., 2008; Varvel et al., 2007) are based on data collected between growth stage V11 and V15 suggesting that variability expression is later in the growing season in Nebraska as well.

Overall the amber sensor had slightly higher R^2 values across each growth stage than the red sensor in site year 1. However, these differences are not substantial and do not suggest that the either sensor is superior to the other under field conditions.

Site-Year 2 NDVI :

The results for site-year 2 follow the trends of site-year 1 very closely. The amber sensor (Table 3.2, Figure 3.5) again had a different NDVI range than the red sensor (Table 3.3, Figure 3.6) but both had high linear relationships of NDVI with applied N rate. At maize growth stage V8 we again saw increased NDVI from the 0 to 50 kg ha^{-1} N rates and then a plateau across all other rates for the amber and red sensors. Trends also were similar at the V10, V12 and V14 growth stages when comparing site-years 1 and 2. Figures 3.5 (amber) and 3.6 (red) show that NDVI increased for each sensor across the 0, 50 and 100 kg ha^{-1} N application rates and then reached a plateau across the 100 and 175 kg ha^{-1} N treatments. As with site-year 1, site-year 2 also reached N sufficiency at the 100 kg ha^{-1} N application rate, since maize grain yields did not increase with increased N application (Table 3.1, Figure 3.2). Therefore we would expect the NDVI values to plateau at the upper two N rates as they did with yield.

The highest linear relationship of NDVI to applied N rate for site-year 2 was observed at the V12 maize growth stage with R^2 values of 0.95 and 0.88 for the amber (Figure 3.5) and red (Figure 3.6) sensors, respectively. Linear relationships were also high at the V14 maize growth stage with R^2 values of 0.86 and 0.82 for the amber and red sensors, respectively. 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., 2004) sensors. The R^2 values observed suggest that V12 to V14 should be the growth stage range in which management decisions based on NDVI readings should be made in northern Colorado.

NDVI and Ancillary Variable Linear Relations:

After establishing sensor performance characteristics the next step was to determine if measurable ancillary crop or soil variables (total plant N, SPAD chlorophyll, plant height and soil NO_3) used in conjunction with NDVI could improve the N status prediction accuracy of each sensor. This was accomplished by regressing NDVI across maize grain yields to determine NDVI to grain yield linear relationships and then performing stepwise regressions using NDVI and all measured ancillary variables to determine if multiple regression relationships increased the relationship with grain yield. This process was repeated over the V8, V10, V12 and V14 maize growth stages to determine if the multiple regressions were growth stage sensitive.

Results indicate that NDVI has a high linear relationship with maize grain yield at the V12 and V14 maize growth stages (Table 3.4), and overall R^2 values were higher for site-year 2 than for site-year 1. Linear relationships of NDVI with grain yield increased as maize growth stage progressed for both the amber and red sensors in both site years (Table 3.4). 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 are able to distinguish this variability within this growth stage range. The linear relationships for site-year 1 are much 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.

Overall our NDVI linear relationships with grain yield are similar to what other researchers have reported. Teal et al. (2006) found red NDVI linear relationships with maize yield in the high seventies ($R^2 = 0.77$), 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. This variability can make it very difficult to direct N recommendations using grain yield linear relationships alone.

Our stepwise multiple regression analysis indicated that only three significant multiple regressions relationships existed (Table 3.4). The first was found in site-year 2 at maize growth stage V10 with amber NDVI and leaf N content. This regression had an R^2 of 0.89 which represents a small improvement relative to NDVI alone, but is not substantially greater than the R^2 of NDVI alone observed at the V12 and V14 growth stages in site-year 2 (Table 3.4). The second significant multiple regression was found in site-year 1 at the V12 maize growth stage. This regression included soil NO_3 and total leaf N contents and had an R^2 of 0.84 (Table 3.4); however, soil NO_3 content did not have a linear relationship with grain yield in any significant way at any maize growth stage at either site year, we believe this result to be an artifact of the data. The final significant multiple regression was found in site-year 2 at the V14 maize growth stage. This regression included amber NDVI, leaf N content, and plant height variables and resulted in an R^2 of 0.95 (Table 3.4). While this multiple regression was an improvement over amber NDVI alone, it was not substantially higher than the R^2 of .91 observed with the red sensor at this growth stage.

Our results suggest that none of the ancillary variables tested would substantially improve the effectiveness of either active sensor or improve the accuracy of an N estimation algorithm that is based on NDVI alone. Sudduth et al. (2009) performed a study incorporating variables such as soil EC, topography, weather, and/or remote sensing data into algorithms and has shown an advantage to using auxiliary information such as soil EC in recommendations on more highly variable river alluvium fields. In our case adding ancillary variables only served to complicate an algorithm by increasing the number of variables needed, some of which are time consuming to measure and can be destructive to the plant. However, our results confirm those found with the N application linear relationships, that V12 to V14 is the best time to used NDVI data to determine in field variability in Colorado.

Nitrogen Recommendation Algorithm:

The amber and red sensors both had high R^2 values in linear relationships with applied N and grain yield at the V12 and V14 maize growth stages. This suggests that V12 to V14 would be the optimum time to use NDVI readings in an N recommendation algorithm. However, any N algorithm should be used as early as possible in the growing season to make subsequent N applications easier to perform when smaller plant sizes allow for easier access to the field with N application equipment. Therefore, our N algorithm was developed for use at the V12 maize growth stage. Since both sensors performed equally well, the N recommendation algorithms were developed for each sensor using the same methodology.

As with other N recommendation algorithms (Tubana et al., 2008; Solari et al., 2008; Varvel et al., 2007; Kitchen et al., 2006) our amber and red sensor N recommendation algorithms were based on a RI. One method for determining RI is presented above in Equation 2, and it is the RI used by Tubana et al. (2008) and Raun et al. (2002). This RI normalizes NDVI data. Equation 2 is also the format used to determine RI in the algorithms presented in this paper. As explained in the materials and methods section, a RI was calculated over a range of N application differences (175, 100 and 50 kg ha^{-1}) and then was regressed over the N application difference that created that particular RI. This regression was then used to calculate an N recommendation quadratic equation that predicts crop N need for the amber (Figure 3.7) and red (Figure 3.8) NDVI sensors. The resulting N recommendation algorithms for each active sensor are as follows:

Amber Sensor:

$$\text{N Rate (kg ha}^{-1}) = (114.1 \times (NDVI_{Reference} / NDVI_{Target})^2) - (118.1 \times (NDVI_{Reference} / NDVI_{Target})) + 1 \qquad \text{[Eq. 5]}$$

Red Sensor:

$$\text{N Rate (kg ha}^{-1}) = (135.3 \times (NDVI_{Reference} / NDVI_{Target})^2) - (134.8 \times (NDVI_{Reference} / NDVI_{Target})) + 1 \qquad \text{[Eq. 6]}$$

The premise for the algorithm methodology we used was that RI is directly related to N differences in the crop. The RI can therefore be used to predict the amount of N it would take to make up this difference, which can be used as the N recommendation. This methodology shares aspects from an algorithm developed by Varvel et al., 2007. The primary differences are that the algorithms shown in Equations 5 and 6 use Equation 2 as the RI and it is specific to growth stage V12 while the Varvel et al. (2007) algorithm uses a sufficiency index (target / reference) and was created over a wide range of maize growth stages using SPAD chlorophyll meter readings and was later adapted to an amber NDVI algorithm by Solari et al. (2008). The algorithms presented in this paper were developed specifically for the amber and red sensors at a specific growth stage of maize.

Both the amber and red NDVI algorithms presented in Equations 5 and 6 were unbiased based on the confidence interval fitting process. A very high percentage of the bootstrapped N recommendations fit within the 95% confidence intervals of the actual N recommendations (Table 3.5). In site-year 1 the amber sensor algorithm bootstrapped N recommendation fit percentages of 96, 89, 95 and 96% were found for the 0, 50, 100 and 175 kg ha^{-1} plots, respectively. Similar values were observed for the red sensor algorithm with 96, 97, 96 and 92% fit found for the 0, 50, 100 and 175 kg ha^{-1} plots, respectively (Table 3.5). This also was the case for site-year 2 where fit percentages for the amber algorithm of 90, 97, 94 and 95% were found across the 0, 50, 100 and 175 kg ha^{-1} plots and fit percentages of 94, 95, 93 and 91% were found for the red sensor algorithm (Table 3.5). Our data clearly show that the amber and red sensor algorithms presented in Equations 5 and 6 are unbiased and are a sound methodology for determining NDVI based N recommendation algorithms. This process represents a good first step for algorithm development in Colorado.

Sensor Algorithm Comparison:

Recommendations from the amber and red sensor algorithms were compared to determine if either sensor recommended significantly different amounts of N fertilizer. Supplemental growth stage V12 N recommendations based on the amber and red sensor algorithms are shown in Table 3.5 and in Figures 3.9 and 3.10 for site-years 1 and 2, respectively. In site-year 1 the amber algorithm recommended 130 kg ha^{-1} and the red algorithm recommended 124 kg ha^{-1} of supplemental N at growth stage V12 on the 0 kg ha^{-1} N plots (applied at emergence) (Table 3.5, Figure 3.9). These values were not statistically or agronomically different. On the 50 kg ha^{-1} N plots the NDVI readings at V12 resulted in identical supplemental N recommendations of 28 kg ha^{-1} for both sensors. When added to the 50 kg ha^{-1} that was applied at emergence the total applied N for these plots would be 78 kg ha^{-1}. On the 100 and 175 kg ha^{-1} N plots the algorithm recommendations were 13 and 6 kg ha^{-1}, respectively, for the amber sensor and 6 and 8 kg ha^{-1}, respectively, for the red sensor. The recommendations for the 100 and 175 kg ha^{-1} plots were not significantly different across sensors or N rates. Recommendation levels at the latter two N rates are so low that under farming conditions no additional N would be applied.

The results for site-year 2 follow the same trends as site-year 1. The NDVI readings on the 0 and 50 kg ha^{-1} N plots resulted in supplemental N recommendations for the amber and red sensor algorithms that were not significantly different from each other with N recommendations of 122 and 116 kg ha^{-1} for the amber and red sensors (Table 3.5

Figure 3.10), respectively, on the 0 kg ha^{-1} plots and 29 and 26 kg ha^{-1} for the amber and red sensors, respectively, on the 50 kg ha^{-1} plots. The NDVI readings from the 100 and 175 kg ha^{-1} N plots also did not differ across sensor type or N rate. The N recommendations were so low that no additional N would be applied. Overall, there were no significant differences in N recommendations between the amber and red algorithms for site-years 1 or 2, suggesting that both sensors perform equally for N recommendations. However, each algorithm is specific to the particular sensor and they can not be used interchangeably or at growth stages other than V12.

CONCLUSIONS

The amber sensor had slightly higher linear relationships with applied N application rate than the red sensor. However, the difference between sensors was not great enough to suggest that one performed better than the other under field conditions. Each sensor had very high NDVI to applied N rate linear relationships ($R^2 > 0.89$), and both sensors were able to determine maize N variability across 2 site-years. Either sensor performed well in determining N variability in maize grown under irrigated conditions in Colorado and either would be a good basis for an N application algorithm. Numerically the highest R^2 values occurred at the V14 maize growth stage for site-year 1 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 time to take NDVI readings in Colorado is in the V12 to V14 maize growth stage range for the most accurate determination of N variability.

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. Therefore, amber and red N recommendation algorithms were developed for use at the V12 maize growth stage using only NDVI readings. The algorithms are as follows:

Amber Sensor:

N Rate (kg ha^{-1}) = (114.1 x ($NDVI_{Reference}$ / $NDVI_{Target}$)^2) – (118.1 x ($NDVI_{Reference}$ / $NDVI_{Target}$)) + 1 [Eq. 5]

Red Sensor:

N Rate (kg ha^{-1}) = (135.3 x ($NDVI_{Reference}$ / $NDVI_{Target}$)^2) – (134.8 x ($NDVI_{Reference}$ / $NDVI_{Target}$)) + 1 [Eq. 6]

The amber and red algorithms did not recommend significantly different amounts of N, and both proved to be unbiased in their N recommendations. This suggests that the NDVI N algorithm development methodology presented in this paper is sound and should be researched further to determine their accuracy over a larger data base that includes more spatial and temporal variability.

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 in and could be very important tools for determining in-season maize N requirements. The integration of these sensors and the appropriate N application algorithms into an on-the-go fertilizer application system should increase the spatial accuracy of N application on fields that are spatially variable if these algorithms are shown to be stable over time and space.

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Table 3.1. Maize grain yield at site years 1 and 2 across 0, 50, 100 and 175 kg ha^{-1} Nitrogen application rates.

Site Year 1

	Nitrogen Rate (kg ha^{-1})			
	0	50	100	175
Yield (Mg ha^{-1})	3.7	6.9	8.5	10.4

Analysis of Variance	P > F	$LSD_{0.10}$
Yield	0.0006	2.3

Site Year 2

	Nitrogen Rate (kg ha^{-1})			
	0	50	100	175
Yield (Mg ha^{-1})	3.4	6.3	7.1	7.3

Analysis of Variance	P > F	$LSD_{0.10}$
Yield	<.0001	0.5

Table 3.2. Amber NDVI readings in irrigated maize for site years 1 and 2 across 4 maize growth stages and 4 applied Nitrogen rates.

Site Year 1

	Nitrogen Rate (kg ha^{-1})			
	0	50	100	175
	--------------------Amber NDVI--------------------			
Corn Growth Stage				
V8	0.270	0.415	0.429	0.414
V10	0.384	0.545	0.581	0.594
V12	0.374	0.552	0.607	0.642
V14	0.550	0.653	0.691	0.705
Analysis of Variance	**P > F**	**LSD $_{0.10}$**		
Rate	<0.0001	0.016		
Growth Stage	<0.0001	0.017		
N Rate x Growth Stage	<0.0001	0.031		

Site Year 2

	Nitrogen Rate (kg ha^{-1})			
	0	50	100	175
	--------------------Amber NDVI--------------------			
Corn Growth Stage				
V8	0.341	0.434	0.448	0.438
V10	0.430	0.559	0.586	0.611
V12	0.382	0.547	0.625	0.643
V14	0.533	0.626	0.676	0.687
Analysis of Variance	**P > F**	**LSD $_{0.10}$**		
Rate	<0.0001	0.018		
Growth Stage	<0.0001	0.020		
N Rate x Growth Stage	<0.0001	0.036		

Table 3.3. Red NDVI readings in irrigated maize for site years 1 and 2 across 4 maize growth stages and 4 applied Nitrogen rates.

Site Year 1

	Nitrogen Rate (kg ha^{-1})			
	0	50	100	175
	----------Red NDVI----------			
Corn Growth Stage				
V8	0.244	0.348	0.350	0.365
V10	0.412	0.614	0.632	0.647
V12	0.477	0.687	0.731	0.759
V14	0.696	0.803	0.853	0.860
Analysis of Variance	**P > F**	**LSD 0.10**		
Rate	<0.0001	0.018		
Growth Stage	<0.0001	0.018		
N Rate x Growth Stage	<0.0001	0.032		

Site Year 2

	Nitrogen Rate (kg ha^{-1})			
	0	50	100	175
	----------Red NDVI----------			
Corn Growth Stage				
V8	0.328	0.421	0.440	0.434
V10	0.481	0.637	0.657	0.689
V12	0.491	0.686	0.753	0.760
V14	0.688	0.807	0.832	0.835
Analysis of Variance	**P > F**	**LSD 0.10**		
Rate	<0.0001	0.026		
Growth Stage	<0.0001	0.026		
N Rate x Growth Stage	0.0059	0.047		

Table 3.4. 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	Site Year 2
V8 Variable Correlation	----------------------------------**R-square**	----------------------------------
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	----------------------------------**R-square**	----------------------------------
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	----------	.89 (amber NDVI + Leaf N)
V12 Variable Correlation	----------------------------------**R-square**	----------------------------------
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	----------------------------------**R-square**	----------------------------------
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	----------	.95 (amber NDVI + Leaf N + Ht)

Table 3.5. Amber and red NDVI algorithm N recommendations at maize growth stage V12 across 4 N application rates (applied at emergence) and the associated 95% confidence interval of each recommendation, the percentage of 100 bootstrapped random samples that fit within the confidence interval and the variance of the 100 bootstrapped random sample N recommendations at site years 1 and 2.

	-----N applied at corn emergence (kg ha^{-1})-----			
Site Year 1	**0**	**50**	**100**	**175**
Amber Algorithm				
Algorithm N Recommendation at V12 (kg ha^{-1})	130	28	13	6
95% Confidence Interval (CI) (Max / Min)	134 / 125	32 / 24	16 / 10	8 / 4
% of Bootstrapped† Samples Within CI	96	89	95	96
Variance of Bootstrapped† N Recommendations	5.2	5.0	2.1	1.4
Red Algorithm				
Algorithm N Recommendation at V12 (kg ha^{-1})	124	28	14	8
95% Confidence Interval (CI) (Max / Min)	129 / 120	32 / 23	17 / 11	10 / 6
% of Bootstrapped† Samples Within CI	96	97	96	92
Variance of Bootstrapped† N Recommendations	7.3	4.0	2.2	0.8

†100 Bootstrapped Random Samples per N Application Rate

	-----N applied at corn emergence (kg ha^{-1})-----			
Site Year 2	**0**	**50**	**100**	**175**
Amber Algorithm				
Algorithm N Recommendation at V12 (kg ha^{-1})	122	29	8	5
95% Confidence Interval (CI) (Max / Min)	126 / 117	33 / 25	11 / 6	6 / 4
% of Bootstrapped† Samples Within CI	90	97	94	95
Variance of Bootstrapped† N Recommendations	7.2	3.5	1.2	0.4
Red Algorithm				
Algorithm N Recommendation at V12 (kg ha^{-1})	116	26	7	7
95% Confidence Interval (CI) (Max / Min)	122 / 111	29 / 22	8 / 6	9 / 5
% of Bootstrapped† Samples Within CI	94	95	93	91
Variance of Bootstrapped† N Recommendations	7.4	4.2	0.6	1.3

†100 Bootstrapped Random Samples per N Application Rate

Figure 3.1. Maize grain yield across 4 applied Nitrogen rates at site year 1.

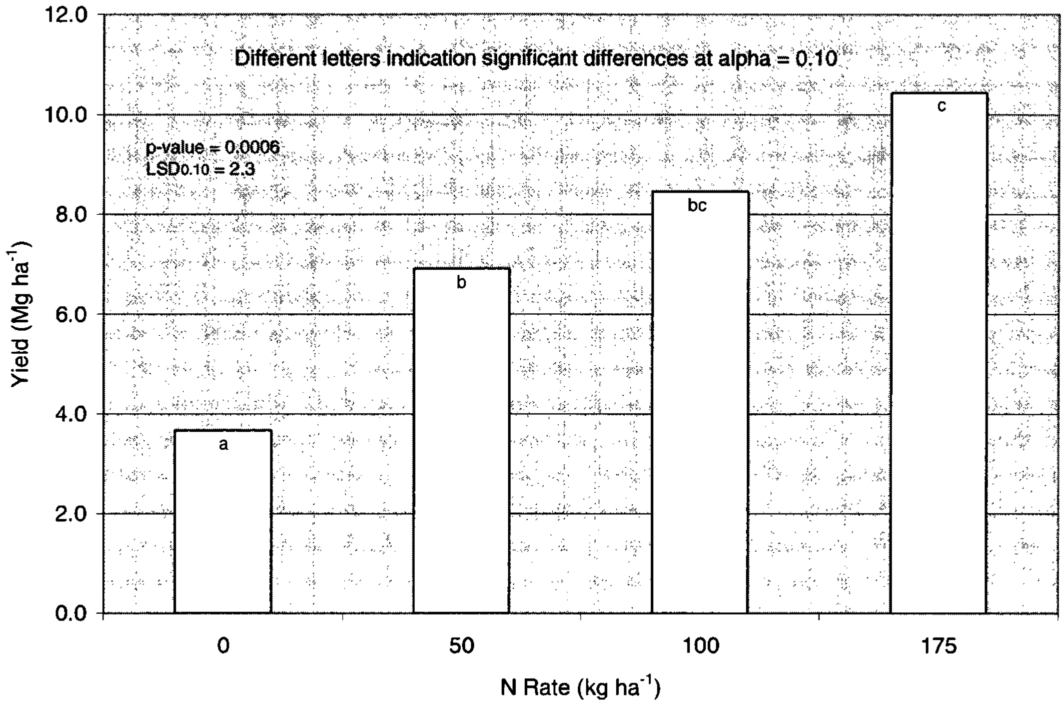


Figure 3.2. Maize grain yield across 4 applied Nitrogen rates at site year 2.

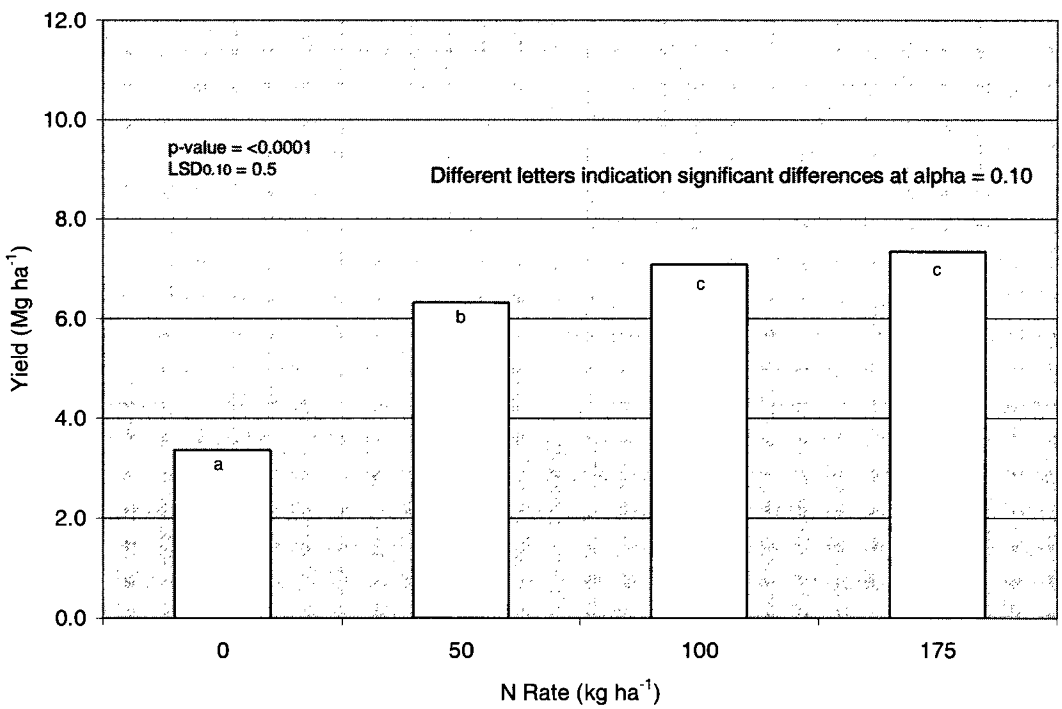


Figure 3.3. Amber NDVI linear relationship with 4 applied Nitrogen rates across 4 maize growth stages for site year 1.

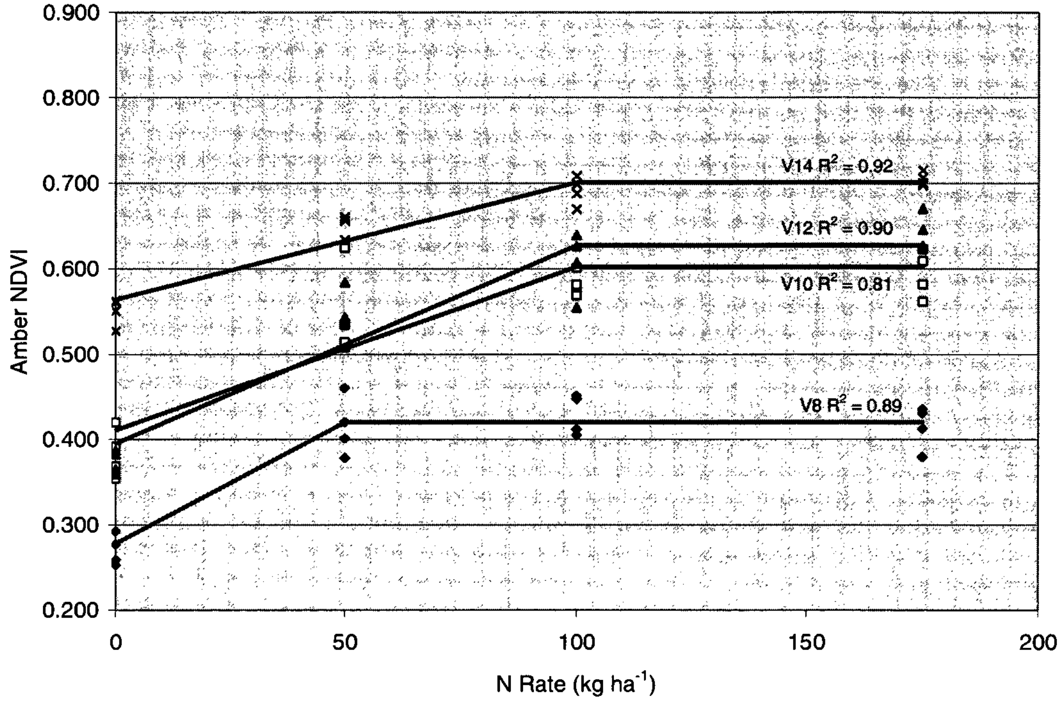


Figure 3.4. Red NDVI linear relationship with 4 applied Nitrogen rates across 4 maize growth stages for site year 1.

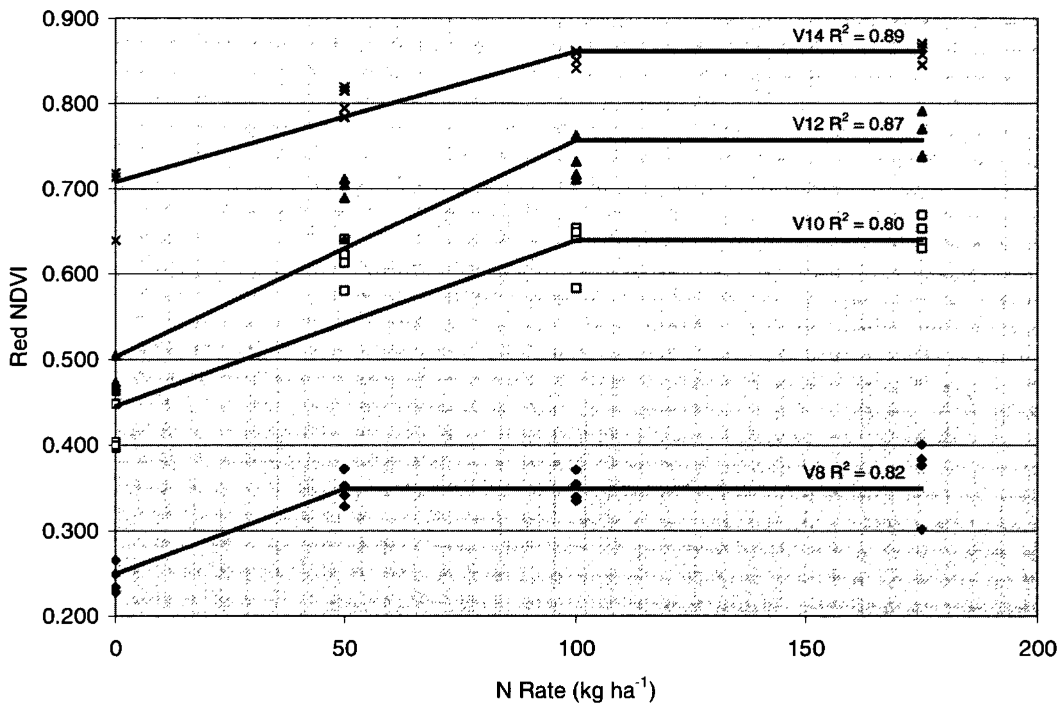


Figure 3.5. Amber NDVI linear relationship with 4 applied Nitrogen rates across 4 maize growth stages for site year 2.

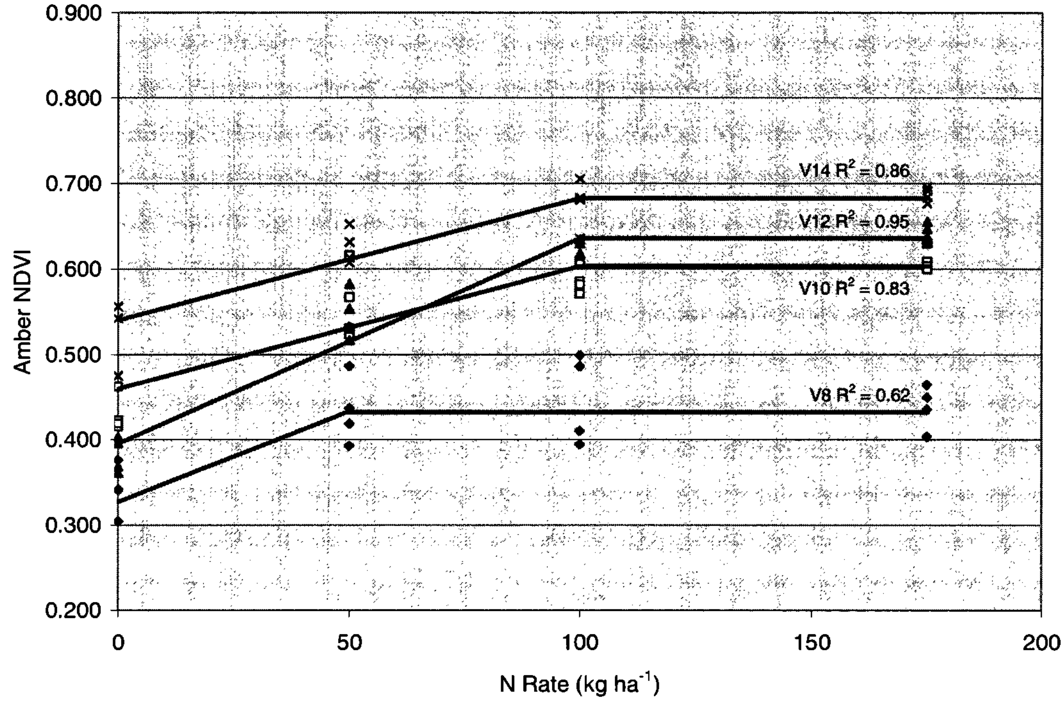


Figure 3.6. Red NDVI linear relationship with 4 applied Nitrogen rates across 4 maize growth stages for site year 2.

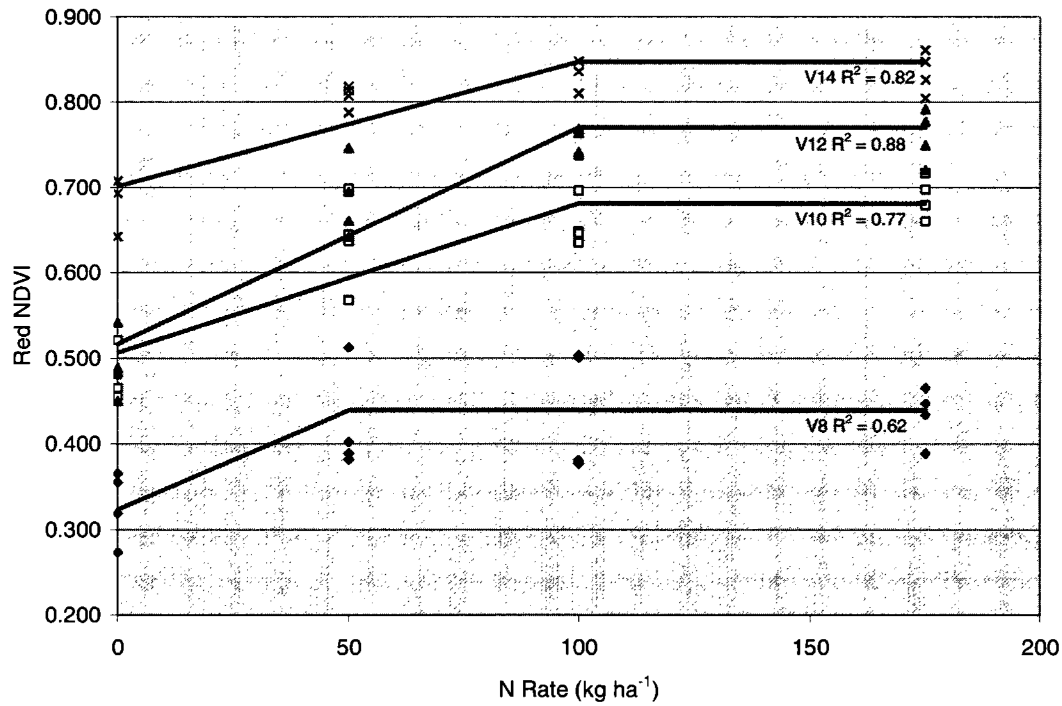


Figure 3.7. Amber NDVI N application algorithm based on V12 maize growth N response to N application rates of 175, 100, 50 and 0 kg ha-1.

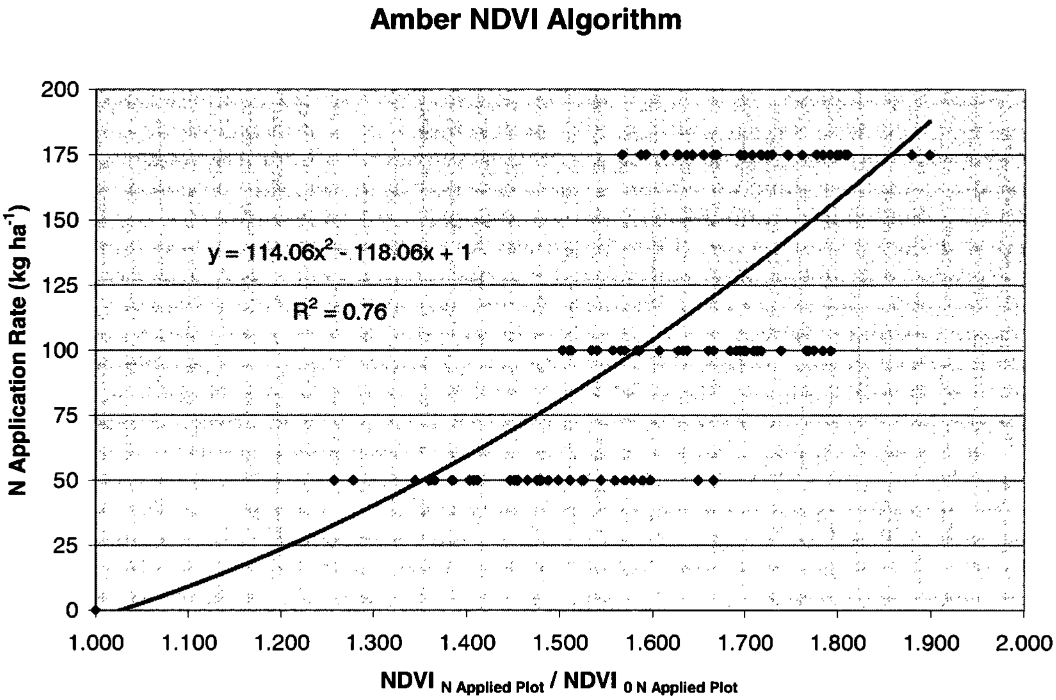


Figure 3.8. Red NDVI N application algorithm based on V12 maize growth N response to N application rates of 175, 100, 50 and 0 kg ha-1.

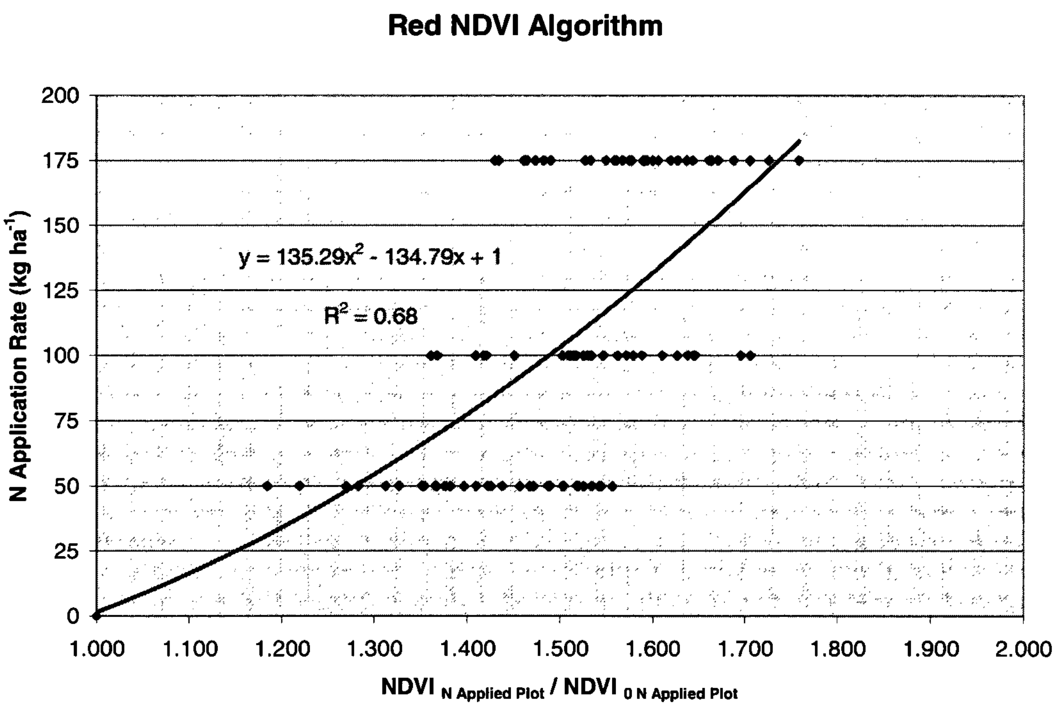


Figure 3.9. Amber and Red NDVI algorithm N recommendations based on NDVI readings collected at V12 for site year 1 across four N rates applied at corn emergence.

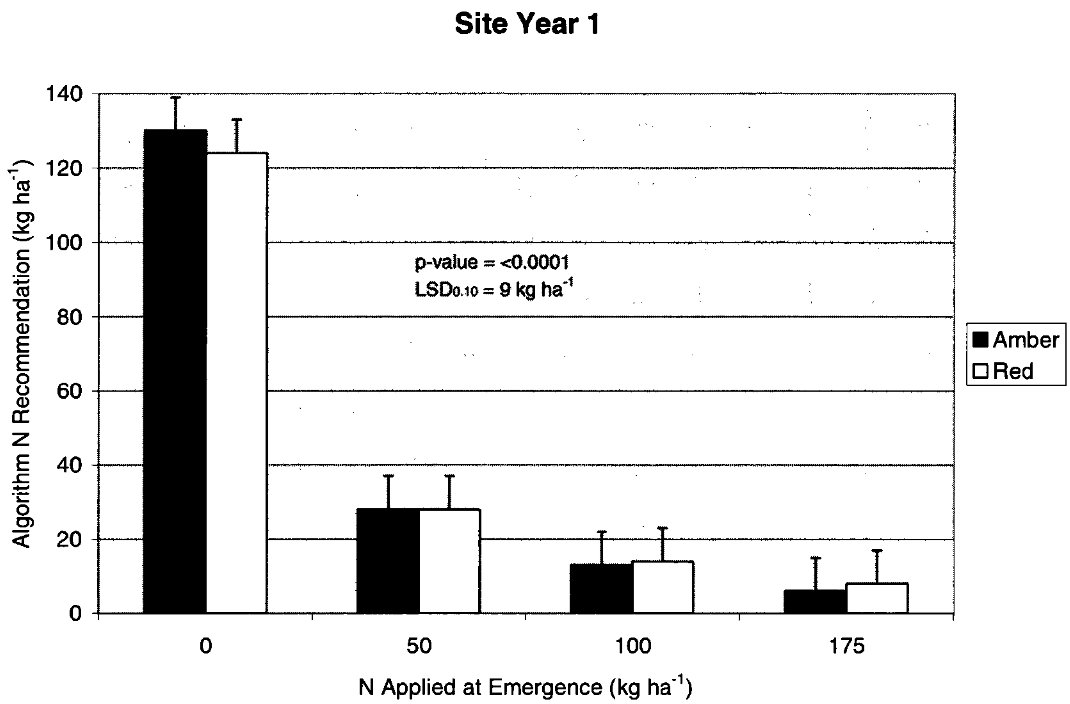
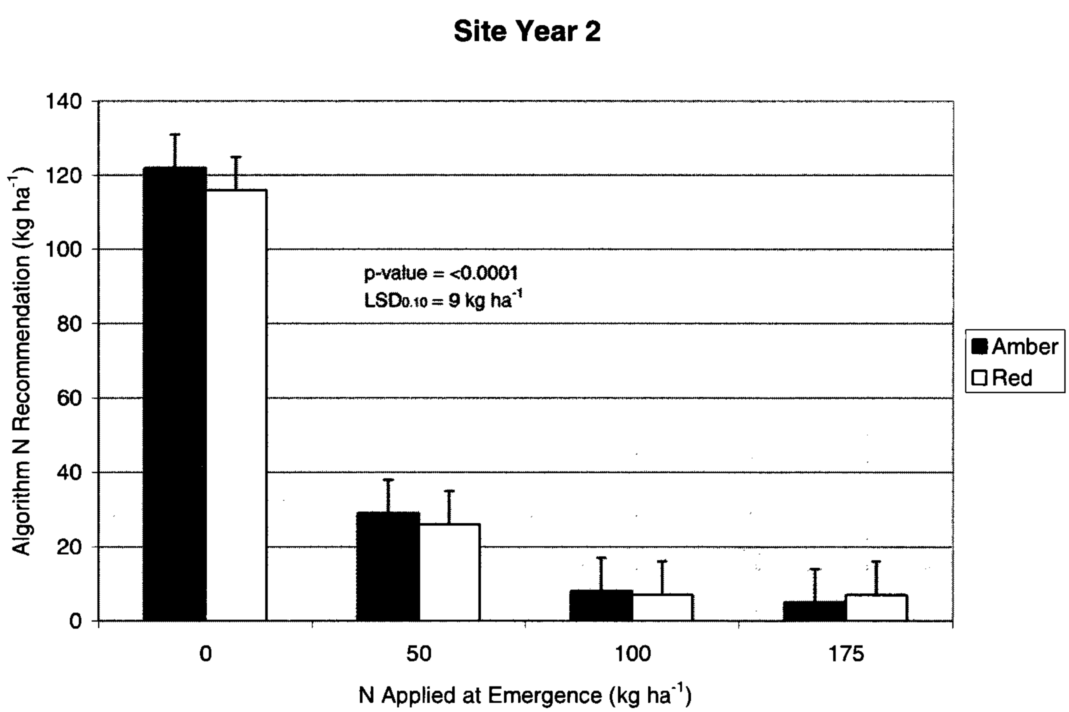


Figure 3.10. Amber and Red NDVI algorithm N recommendations based on NDVI readings collected at V12 for site year 2 across four N rates applied at corn emergence.



APPENDIX A

Table A1.1. Management zone residual analysis by site year and growth stage.

Growth Stage	Site Year	Management Zone	GNDVI Residual	SPAD Redsidual	Plant Height Residual
V8	ARDEC 2004	High	0.0039 a	-----	-----
		Medium	-0.0104 b	-----	-----
		Low	0.0082 a	-----	-----
	p-value ($LSD_{0.10}$)		0.0304 (0.0066)	-----	-----
	Yuma 2004	High	-----	-----	-----
		Medium	-----	-----	-----
		Low	-----	-----	-----
	p-value ($LSD_{0.10}$)		-----	-----	-----
	ARDEC 2005	High	-0.1255	2.10 a	-61.28
		Medium	-0.1196	-2.12 b	-60.46
		Low	-0.1099	-3.75 c	-62.15
	p-value ($LSD_{0.10}$)		0.3788	<0.0001 (1.29)	0.1366
	Lucerne 2005	High	-0.1577 a	-4.03 ab	-55.51 ab
		Medium	-0.1372 b	-4.77 b	-54.02 a
		Low	-0.1389 b	-3.52 a	-57.99 b
	p-value ($LSD_{0.10}$)		0.0068 (0.0116)	0.0770 (0.91)	0.0699 (2.85)
V12	ARDEC 2004	High	0.0169 a	-----	-----
		Medium	-0.0544 b	-----	-----
		Low	-0.0115 b	-----	-----
	p-value ($LSD_{0.10}$)		0.0011 (0.0126)	-----	-----
	Yuma 2004	High	0.0033	-----	-----
		Medium	0.0092	-----	-----
		Low	-0.0125	-----	-----
	p-value ($LSD_{0.10}$)		0.1705	-----	-----
	ARDEC 2005	High	0.0330 a	0.99 a	9.66 a
		Medium	0.0199 b	-0.71 b	4.33 b
		Low	0.0131 b	-1.56 c	-4.86 c
	p-value ($LSD_{0.10}$)		<0.0001 (0.0156)	0.004 (1.25)	<0.0001 (2.74)
	Lucerne 2005	High	-0.0036	2.88 a	15.01
		Medium	-0.0057	-1.24 b	7.59
		Low	-0.0123	-0.08 c	-3.91
	p-value ($LSD_{0.10}$)		0.3841	<0.0001 (1.06)	0.1169
V16	ARDEC 2004	High	-----	-----	-----
		Medium	-----	-----	-----
		Low	-----	-----	-----
	p-value ($LSD_{0.10}$)		-----	-----	-----
	Yuma 2004	High	-----	-----	-----
		Medium	-----	-----	-----
		Low	-----	-----	-----
	p-value ($LSD_{0.10}$)		-----	-----	-----
	ARDEC 2005	High	0.1420	5.21 a	62.52 a
		Medium	0.1768	1.56 b	62.35 a
		Low	0.1737	-1.73 c	49.89 b
	p-value ($LSD_{0.10}$)		0.1791	<0.0001 (2.03)	0.0004 (5.77)
	Lucerne 2005	High	0.1600	4.89 a	53.77 a
		Medium	0.1503	3.80 a	59.26 a
		Low	0.1450	1.95 b	42.89 b
	p-value ($LSD_{0.10}$)		0.5000	0.0046 (1.03)	<0.0001 (4.15)

Table A1.2. Maize grain yield residual analysis by management zone and site year.

Site Year	Management Zone	Yield Residual
ARDEC 2004	High	9.82 a
	Medium	1.58 a
	Low	-11.40 b
p-value ($LSD_{0.10}$)		0.0065 (10.70)
Yuma 2004	High	47.39 a
	Medium	-4.71 b
	Low	-42.68 c
p-value ($LSD_{0.10}$)		<0.0001 (19.66)
ARDEC 2005	High	14.78 a
	Medium	6.04 a
	Low	-20.82 b
p-value ($LSD_{0.10}$)		<0.0001 (10.77)
Lucerne 2005	High	-9.26
	Medium	9.27
	Low	-0.01
p-value ($LSD_{0.10}$)		0.2574

Table A1.3. N application treatment rates for site years 1 and 2 across management zone (MZ).

	Site year 1 (ARDEC 2004)			
	N Rate (Factor of soil test recommendation)			
	0 x N rec.	0.5 x N rec	1.0 x N rec	1.5 x N rec
	---------------------------kg N ha^{-1}---------------------------			
MZ				
High	0	30	65	100
Medium	0	60	120	185
Low	0	50	100	155

	Site year 2 (Yuma 2004)			
	N Rate (Factor of soil test recommendation)			
	0 x N rec.	0.5 x N rec	1.0 x N rec	1.5 x N rec
	---------------------------kg N ha^{-1}---------------------------			
MZ				
High	0	95	90	280
Medium	0	75	150	230
Low	0	50	100	150

Table A1.4. Site Year 1 (ARDEC 2004) GNDVI at maize growth stages V8 and V12 as affected by N application rate and management zone (MZ).

V8 Growth Stage	N Rate (Factor of soil test recommendation)				
	0 x N rec.	0.5 x N rec	1.0 x N rec	1.5 x N rec	
	----GNDVI----				
Rate Average	0.415	0.430	0.418	0.412	
MZ					**Zone Avg.**
High	0.432	0.435	0.402	0.410	0.417
Medium	0.426	0.432	0.420	0.429	0.426
Low	0.388	0.423	0.432	0.398	0.412

Analysis of Variance	**P > F**	**$LSD_{0.10}$**
Rate	0.1460	---
MZ	0.0467	0.009
Rate x MZ	0.0123	0.008

V12 Growth Stage	N Rate (Factor of soil test recommendation)				
	0 x N rec.	0.5 x N rec	1.0 x N rec	1.5 x N rec	
	----GNDVI----				
Rate Average	0.403	0.412	0.408	0.413	
MZ					**Zone Avg.**
High	0.405	0.435	0.426	0.414	0.422
Medium	0.400	0.403	0.412	0.404	0.405
Low	0.404	0.398	0.387	0.411	0.398

Analysis of Variance	**P > F**	**$LSD_{0.10}$**
Rate	0.7623	---
MZ	0.0028	0.011
Rate x MZ	0.2888	---

Table A1.5. Site Year 1 (ARDEC 2004) maize grain yield by N treatment and management zone (MZ).

	N Rate (Factor of soil test recommendation)				
	0 x N rec.	0.5 x N rec	1.0 x N rec	1.5 x N rec	
	------Mg ha^{-1}------				
Rate Average	5.15	5.95	5.08	5.75	
MZ					**Zone Avg.**
High	6.10	6.22	5.79	6.30	6.1
Medium	5.25	6.94	4.93	5.22	5.6
Low	4.05	4.71	4.54	5.72	4.8

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.1111	---
MZ	0.0015	0.82
Rate x MZ	0.2005	---

Table A1.6. Site Year 2 (Yuma 2004) GNDVI at maize growth stage V12 as affected by N application rate and management zone (MZ).

	N Rate (Factor of soil test recommendation)				
	0 x N rec.	0.5 x N rec	1.0 x N rec	1.5 x N rec	
	------GNDVI------				
Rate Average	0.695	0.67	0.685	0.677	
MZ					**Zone Avg.**
High	0.71	0.667	0.703	0.69	0.696
Medium	0.69	0.678	0.684	0.694	0.686
Low	0.686	0.666	0.666	0.648	0.669

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.4155	---
MZ	0.0506	0.020
Rate x MZ	0.8895	---

Table A1.7. Site Year 2 (Yuma 2004) maize grain yield by N treatment and management zone (MZ).

	N Rate (Factor of soil test recommendation)				
	0 x N rec.	0.5 x N rec	1.0 x N rec	1.5 x N rec	
	---Mg ha^{-1}---				
Rate Average	9.80	9.97	9.25	10.30	
MZ					**Zone Avg.**
High	12.36	12.39	12.15	14.32	12.80
Medium	9.39	9.79	9.62	9.34	9.54
Low	7.64	7.73	5.97	7.26	7.15

Analysis of Variance	**P > F**	**$LSD_{0.10}$**
Rate		---
MZ	<0.0001	1.26
Rate x MZ		---

Table A1.8. Site Year 3 (ARDEC 2005) GNDVI at maize growth stages V8, V12 and V16 as affected by N application rate and management zone (MZ).

GNDVI (V8)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	GNDVI						
Rate Average	0.418	0.427	0.418	0.422	0.399	0.393	
MZ							**Zone Avg.**
High	0.423	0.432	0.412	0.412	0.367	0.388	0.405
Medium	0.402	0.435	0.411	0.431	0.395	0.395	0.411
Low	0.428	0.414	0.431	0.422	0.434	0.397	0.421

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.2899	---
MZ	0.4250	---
Rate x MZ	0.7754	---

GNDVI (V12)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	GNDVI						
Rate Average	0.488	0.484	0.488	0.483	0.498	0.470	
MZ							**Zone Avg.**
High	0.458	0.445	0.450	0.474	0.466	0.422	0.452
Medium	0.503	0.507	0.522	0.491	0.521	0.489	0.505
Low	0.503	0.501	0.493	0.486	0.510	0.498	0.498

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.4399	---
MZ	<0.0001	0.016
Rate x MZ	0.7666	---

GNDVI (V16)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	GNDVI						
Rate Average	0.686	0.717	0.667	0.711	0.705	0.685	
MZ							**Zone Avg.**
High	0.670	0.727	0.641	0.696	0.719	0.587	0.673
Medium	0.693	0.714	0.696	0.723	0.684	0.738	0.708
Low	0.696	0.711	0.664	0.714	0.712	0.732	0.705

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.5870	---
MZ	0.2122	---
Rate x MZ	0.4808	---

Table A1.9. Site Year 3 (ARDEC 2005) SPAD Chlorophyll at maize growth stages V8, V12 and V16 as affected by N application rate and management zone (MZ).

SPAD (V8)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	SPAD						
Rate Average	40.9	40.7	40.6	41.0	41.4	40.8	
MZ							**Zone Avg.**
High	42.4	44.4	43.6	45.9	43.9	45.5	44.3
Medium	39.0	38.2	39.1	36.4	39.9	38.0	40.0
Low	41.2	39.5	39.3	40.7	40.6	39.1	38.4

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.9619	---
MZ	<0.0001	1.1
Rate x MZ	0.2127	---

SPAD (V12)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	SPAD						
Rate Average	39.1	39.7	42.1	42.2	43.6	43.8	
MZ							**Zone Avg.**
High	42.5	41.5	42.7	44.1	43.5	44.7	43.2
Medium	38.4	38.9	42.0	41.6	43.7	44.2	41.5
Low	36.5	38.8	41.5	40.8	43.7	42.5	40.6

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	<0.0001	1.7
MZ	0.0036	1.2
Rate x MZ	0.5292	---

SPAD (V16)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	SPAD						
Rate Average	43.9	41.2	43.5	43.8	44.3	46.3	
MZ							**Zone Avg.**
High	49.6	46.8	47.5	48.8	44.7	46.9	47.4
Medium	45.6	37.7	43.3	43.6	43.6	48.6	43.7
Low	36.6	39.1	39.8	39.1	44.6	43.5	40.4

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.1084	---
MZ	<0.0001	1.94
Rate x MZ	0.0435	1.87

Table A1.10. Site Year 3 (ARDEC 2005) plant height at maize growth stages V8, V12 and V16 as affected by N application rate and management zone (MZ).

Plant Height (V8)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	Height (cm)						
Rate Average	44.8	43.4	45.8	45.8	45.1	44.5	
MZ							**Zone Avg.**
High	44.0	43.4	46.6	45.8	46.2	43.8	44.9
Medium	43.9	44.3	47.3	47.1	45.5	46.5	45.7
Low	46.6	42.5	43.7	44.6	43.7	43.3	44.1

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.2456	---
MZ	0.1080	---
Rate x MZ	0.5223	---

Plant Height (V12)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	Height (cm)						
Rate Average	109.0	105.2	108.2	109.7	112.6	110.8	
MZ							**Zone Avg.**
High	115.1	116.5	114.3	114.1	119.3	115.9	115.9
Medium	107.8	102.5	108.4	115.4	113.2	116.0	110.5
Low	104.0	96.8	101.9	99.7	105.3	100.5	101.3

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.0544	3.9
MZ	<0.0001	2.8
Rate x MZ	0.1994	---

Plant Height (V16)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	Height (cm)						
Rate Average	166.9	158.4	166.1	163.4	166.4	165.6	
MZ							**Zone Avg.**
High	172.1	162.9	173.7	169.5	164.3	168.9	168.6
Medium	177.4	157.7	175.5	171.5	165.4	164.9	168.7
Low	151.2	154.5	149.3	149.2	169.6	162.9	156.1

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.4827	---
MZ	0.0005	5.79
Rate x MZ	0.1821	---

Table A1.11. Site Year 3 (ARDEC 2005) maize grain yield by N treatment and management zone (MZ).

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	Yield (Mg ha^{-1})						
Rate Average	6.80	6.96	7.80	8.46	9.05	9.23	
MZ							**Zone Avg.**
High	8.17	9.09	9.09	8.43	9.83	9.33	8.99
Medium	7.09	6.10	8.16	10.05	8.67	10.58	8.44
Low	5.15	5.89	6.16	6.91	8.66	7.76	6.76

Analysis of Variance	**P > F**	**$LSD_{0.10}$**
Rate	<0.0001	0.94
MZ	<0.0001	0.66
Rate x MZ	0.0606	0.60

Table A1.12. Site Year 4 (Lucerne 2005) GNDVI at maize growth stages V8, V12 and V16 as affected by N application rate and management zone (MZ).

GNDVI (V8)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	GNDVI						
Rate Average	0.422	0.421	0.430	0.419	0.415	0.432	
MZ							**Zone Avg.**
High	0.424	0.414	0.414	0.396	0.408	0.402	0.410
Medium	0.423	0.421	0.444	0.439	0.413	0.442	0.431
Low	0.416	0.429	0.432	0.421	0.425	0.452	0.429

Analysis of Variance	P > F	LSD0.10
Rate	0.4874	---
MZ	0.0067	0.0115
Rate x MZ	0.4306	---

GNDVI (V12)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	GNDVI						
Rate Average	0.563	0.562	0.569	0.555	0.560	0.554	
MZ							**Zone Avg.**
High	0.573	0.569	0.576	0.549	0.573	0.544	0.564
Medium	0.558	0.554	0.580	0.561	0.560	0.559	0.562
Low	0.557	0.552	0.552	0.554	0.547	0.550	0.552

Analysis of Variance	P > F	LSD0.10
Rate	0.5238	---
MZ	0.0756	0.009
Rate x MZ	0.6038	---

GNDVI (V16)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	GNDVI						
Rate Average	0.709	0.718	0.694	0.741	0.743	0.714	
MZ							**Zone Avg.**
High	0.694	0.735	0.713	0.740	0.743	0.743	0.728
Medium	0.733	0.724	0.691	0.760	0.721	0.679	0.718
Low	0.700	0.694	0.677	0.723	0.764	0.719	0.713

Analysis of Variance	P > F	LSD0.10
Rate	0.0622	0.030
MZ	0.4891	---
Rate x MZ	0.3554	---

Table A1.13. Site Year 4 (Lucerne 2005) SPAD Chlorophyll at maize growth stages V8, V12 and V16 as affected by N application rate and management zone (MZ).

SPAD (V8)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	SPAD						
Rate Average	46.7	45.7	45.4	45.6	46.9	45.6	
MZ							**Zone Avg.**
High	46.4	45.1	45.3	46.3	46.7	46.6	46.1
Medium	46.4	45.6	44.9	44.4	46.7	43.9	45.3
Low	47.4	46.5	45.8	46.1	47.5	46.3	46.6

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.2716	---
MZ	0.1102	---
Rate x MZ	0.9381	---

SPAD (V12)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	SPAD						
Rate Average	50.4	50.6	50.5	50.7	51.0	50.4	
MZ							**Zone Avg.**
High	52.1	53.3	52.5	53.4	53.8	52.8	53.0
Medium	49.8	50.3	50.9	49.1	50.1	49.8	50.0
Low	49.4	48.2	48.2	49.7	49.0	48.5	48.8

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.9877	---
MZ	<0.0001	1.07
Rate x MZ	0.9320	---

SPAD (V16)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	SPAD						
Rate Average	52.8	52.8	53.9	53.9	54.8	54.0	
MZ							**Zone Avg.**
High	53.6	51.8	53.5	54.9	60.6	55.5	54.9
Medium	54.4	52.4	54.9	54.8	52.3	54.5	53.9
Low	50.4	54.4	53.4	51.9	51.2	52.0	52.2

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.4594	---
MZ	0.0025	1.27
Rate x MZ	0.0029	1.89

Table A1.14. Site Year 4 (Lucerne 2005) plant height at maize growth stages V8, V12 and V16 as affected by N application rate and site specific management zone (MZ).

Plant Height (V8)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	Height (cm)						
Rate Average	64.2	64.5	63.4	62.7	64.1	63.2	
MZ							**Zone Avg.**
High	65.1	63.4	64.0	64.6	64.4	60.6	64.0
Medium	66.5	67.6	63.9	63.7	65.0	66.4	65.5
Low	61.1	60.5	62.3	59.8	62.9	62.5	61.5

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.8245	---
MZ	0.0019	1.77
Rate x MZ	0.6138	---

Plant Height (V12)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	Height (cm)						
Rate Average	145.3	123.2	123.0	121.6	121.4	120.0	
MZ							**Zone Avg.**
High	191.6	123.7	121.7	121.3	122.9	126.0	134.5
Medium	117.8	117.0	117.0	115.1	115.4	111.5	127.1
Low	126.6	128.9	130.4	128.4	125.9	122.5	115.6

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.3513	---
MZ	0.1198	---
Rate x MZ	0.4150	---

Plant Height (V16)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	Height (cm)						
Rate Average	171.6	176.3	173.8	169.2	171.9	171.7	
MZ							**Zone Avg.**
High	178.0	176.2	179.6	163.6	---	176.0	174.7
Medium	179.4	179.3	180.9	181.8	176.3	175.0	178.8
Low	157.5	173.4	160.8	162.2	167.5	164.2	164.3

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.6729	---
MZ	<.0001	5.01
Rate x MZ	0.3747	---

Table A1.15. Site Year 4 (Lucerne 2005) maize grain yield by N treatment and management zone (MZ).

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	Yield (Mg ha^{-1})						
Rate Average	16.86	17.33	17.99	18.50	17.80	17.55	
MZ							**Zone Avg.**
High	16.17	16.55	16.02	18.18	16.27	16.59	16.62
Medium	17.20	18.23	21.17	17.85	19.20	19.03	18.78
Low	17.20	17.21	16.83	19.48	17.94	17.02	17.61

Analysis of Variance	**P > F**	**$LSD_{0.10}$**
Rate	0.6500	---
MZ	0.0124	1.17
Rate x MZ	0.5629	---

Table A1.16. Site year 1 (ARDEC 2004) GNDVI by sensor at maize growth stage V8 across applied N rate and management zone (MZ).

Sensor #1

	N Rate (Factor of soil test recommendation)				
	0 x N rec.	0.5 x N rec	1.0 x N rec	1.5 x N rec	
	GNDVI				
Rate Average	0.412	0.435	0.417	0.417	
MZ					**Zone Avg.**
High	0.426	0.422	0.393	0.417	0.418
Medium	0.423	0.433	0.419	0.407	0.413
Low	0.393	0.443	0.422	0.427	0.428

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.1829	---
MZ	0.1501	---
Rate x MZ	0.6460	---

Sensor #2

	N Rate (Factor of soil test recommendation)				
	0 x N rec.	0.5 x N rec	1.0 x N rec	1.5 x N rec	
	GNDVI				
Rate Average	0.430	0.451	0.440	0.425	
MZ					**Zone Avg.**
High	0.428	0.446	0.429	0.421	0.430
Medium	0.414	0.448	0.448	0.416	0.432
Low	0.447	0.456	0.435	0.436	0.444

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.1334	---
MZ	0.7094	---
Rate x MZ	0.6649	---

Sensor #3

	N Rate (Factor of soil test recommendation)				
	0 x N rec.	0.5 x N rec	1.0 x N rec	1.5 x N rec	
	GNDVI				
Rate Average	0.422	0.428	0.421	0.410	
MZ					**Zone Avg.**
High	0.448	0.460	0.420	0.418	0.437
Medium	0.396	0.415	0.428	0.388	0.407
Low	0.434	0.425	0.415	0.425	0.425

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.1194	---
MZ	0.0217	0.018
Rate x MZ	0.5478	---

Sensor #4

	N Rate (Factor of soil test recommendation)				
	0 x N rec.	0.5 x N rec	1.0 x N rec	1.5 x N rec	
	GNDVI				
Rate Average	0.385	0.402	0.415	0.387	
MZ					**Zone Avg.**
High	0.425	0.413	0.369	0.381	0.398
Medium	0.350	0.395	0.434	0.348	0.382
Low	0.400	0.403	0.407	0.429	0.410

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.5731	---
MZ	0.0748	0.025
Rate x MZ	0.0220	0.017

Table A1.17. Site year 1 GNDVI (ARDEC 2004) by sensor at maize growth stage V12 across applied N rate and management zone (MZ).

Sensor #1

	N Rate (Factor of soil test recommendation)				
	0 x N rec.	0.5 x N rec	1.0 x N rec	1.5 x N rec	
	----------GNDVI----------				
Rate Average	0.405	0.433	0.432	0.438	
MZ					**Zone Avg.**
High	0.411	0.465	0.472	0.448	0.449
Medium	0.401	0.417	0.411	0.430	0.415
Low	0.404	0.418	0.414	0.438	0.419

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.1371	---
MZ	0.0265	0.022
Rate x MZ	0.7181	---

Sensor #2

	N Rate (Factor of soil test recommendation)				
	0 x N rec.	0.5 x N rec	1.0 x N rec	1.5 x N rec	
	----------GNDVI----------				
Rate Average	0.374	0.353	0.345	0.366	
MZ					**Zone Avg.**
High	0.381	0.351	0.355	0.390	0.369
Medium	0.358	0.358	0.327	0.353	0.349
Low	0.383	0.350	0.355	0.356	0.361

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.0796	0.020
MZ	0.1416	---
Rate x MZ	0.5676	---

Sensor #3

	N Rate (Factor of soil test recommendation)				
	0 x N rec.	0.5 x N rec	1.0 x N rec	1.5 x N rec	
	----------GNDVI----------				
Rate Average	0.416	0.426	0.414	0.411	
MZ					**Zone Avg.**
High	0.418	0.455	0.431	0.401	0.426
Medium	0.417	0.402	0.364	0.407	0.397
Low	0.414	0.420	0.447	0.425	0.426

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.7131	---
MZ	0.0244	0.020
Rate x MZ	0.0784	0.011

Sensor #4

	N Rate (Factor of soil test recommendation)				
	0 x N rec.	0.5 x N rec	1.0 x N rec	1.5 x N rec	
	----------GNDVI----------				
Rate Average	0.416	0.436	0.441	0.430	
MZ					**Zone Avg.**
High	0.408	0.468	0.446	0.413	0.434
Medium	0.441	0.415	0.444	0.436	0.434
Low	0.400	0.425	0.434	0.440	0.425

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.4312	---
MZ	0.7445	---
Rate x MZ	0.2957	---

Table A1.18. Site year 2 (Yuma 2004) GNDVI by sensor at maize growth stage V8 across applied N rate and management zone (MZ).

Sensor #1

	N Rate (Factor of soil test recommendation)				
	0 x N rec.	0.5 x N rec	1.0 x N rec	1.5 x N rec	
	GNDVI				
Rate Average	0.674	0.649	0.659	0.657	
MZ					**Zone Avg.**
High	0.659	0.666	0.666	0.691	0.670
Medium	0.699	0.646	0.687	0.647	0.639
Low	0.664	0.636	0.624	0.633	0.670

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.5550	---
MZ	0.0682	0.025
Rate x MZ	0.4062	---

Sensor #2

	N Rate (Factor of soil test recommendation)				
	0 x N rec.	0.5 x N rec	1.0 x N rec	1.5 x N rec	
	GNDVI				
Rate Average	0.6885	0.6677	0.6745	0.6786	
MZ					**Zone Avg.**
High	0.6857	0.6722	0.6757	0.6893	0.6807
Medium	0.7072	0.6700	0.6970	0.6810	0.6688
Low	0.6727	0.6610	0.6510	0.6655	0.6625

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.6541	---
MZ	0.1918	---
Rate x MZ	0.9627	---

Sensor #3

	N Rate (Factor of soil test recommendation)				
	0 x N rec.	0.5 x N rec	1.0 x N rec	1.5 x N rec	
	GNDVI				
Rate Average	0.7182	0.6953	0.7161	0.7100	
MZ					**Zone Avg.**
High	0.7140	0.6990	0.7137	0.7150	0.7093
Medium	0.7307	0.6905	0.7275	0.7325	0.7203
Low	0.7100	0.6965	0.7070	0.6870	0.7001

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.2044	---
MZ	0.1432	---
Rate x MZ	0.7257	---

Sensor #4

	N Rate (Factor of soil test recommendation)				
	0 x N rec.	0.5 x N rec	1.0 x N rec	1.5 x N rec	
	GNDVI				
Rate Average	0.7005	0.6986	0.6880	0.6833	
MZ					**Zone Avg.**
High	0.7005	0.6755	0.6803	0.6828	0.6848
Medium	0.7035	0.6625	0.7028	0.6940	0.6906
Low	0.6977	0.6680	0.6810	0.6730	0.6799

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.2712	---
MZ	0.7406	---
Rate x MZ	0.9799	---

Table A1.19. Site year 1 (ARDEC 2004) GNDVI by maize growth stage (GS) and nitrogen (N) rate treatment.

	N Rate (Factor of soil test recommendation)				
	0 x N rec.	0.5 x N rec	1.0 x N rec	1.5 x N rec	
	GNDVI				
Rate Average	0.409	0.421	0.413	0.409	
GS					**GS Avg.**
V8	0.415	0.430	0.418	0.410	0.418
V12	0.403	0.412	0.408	0.407	0.408

Analysis of Variance	**P > F**	**$LSD_{0.10}$**
GS	0.1512	---
Rate	0.5961	---
GS x Rate	0.8912	---

Table A1.20. Site year 3 (ARDEC 2005) soil N concentration at maize growth stages V8, V12 and V16 across N application rate and management zone (MZ).

Soil N Conc. (V8)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	Soil N (mg kg^{-1})						
Rate Average	4.92	5.08	5.08	5.50	5.25	4.83	
MZ							**Zone Avg.**
High	6.75	6.00	5.50	6.75	7.25	5.25	6.25
Medium	3.75	4.25	5.50	5.50	3.75	5.00	4.63
Low	4.25	5.00	4.25	4.25	4.75	4.25	4.45

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.8287	---
MZ	<0.0001	0.62
Rate x MZ	0.1588	---

Soil N Conc. (V12)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	Soil N (mg kg^{-1})						
Rate Average	7.67	8.58	11.25	11.08	15.50	9.91	
MZ							**Zone Avg.**
High	9.25	7.50	9.00	9.00	16.75	12.50	10.66
Medium	6.50	12.25	11.75	13.25	11.25	12.50	11.25
Low	7.25	6.00	13.00	11.00	18.50	4.75	10.08

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.2295	---
MZ	0.8853	---
Rate x MZ	0.7045	---

Soil N Conc. (V16)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	Soil N (mg kg^{-1})						
Rate Average	6.16	12.00	11.25	15.50	15.50	17.83	
MZ							**Zone Avg.**
High	6.00	10.25	10.00	15.00	21.50	16.75	13.25
Medium	8.00	16.75	9.25	18.25	11.25	23.75	14.54
Low	4.50	9.00	14.50	13.25	13.75	13.00	11.33

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.0209	5.62
MZ	0.4024	---
Rate x MZ	0.4675	---

Table A1.21. Site year 3 (ARDEC 2005) plant N concentration at maize growth stages V8, V12 and V16 across N rate and management zone (MZ).

Plant N Conc. (V8)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	Plant N (mg kg^{-1})						
Rate Average	14.58	23.50	18.54	14.90	11.45	16.09	
MZ							**Zone Avg.**
High	21.75	32.00	18.75	17.25	12.75	28.75	21.88
Medium	12.25	25.50	18.50	18.33	13.25	8.50	15.96
Low	9.75	13.00	18.33	10.00	7.33	9.33	11.24

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.1597	---
MZ	0.0105	5.32
Rate x MZ	0.5950	---

Plant N Conc. (V12)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	Plant N (mg kg^{-1})						
Rate Average	38.91	41.66	43.47	36.18	37.45	48.73	
MZ							**Zone Avg.**
High	32.25	43.25	35.50	37.75	35.50	36.50	36.79
Medium	50.25	41.00	61.25	40.25	40.25	57.25	48.38
Low	34.25	40.75	32.75	28.66	36.33	53.66	37.48

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.2004	---
MZ	0.0049	6.23
Rate x MZ	0.2939	---

Plant N Conc. (V16)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	Plant N (mg kg^{-1})						
Rate Average	21.08	20.50	20.42	21.25	21.66	22.75	
MZ							**Zone Avg.**
High	19.75	18.75	20.25	18.25	18.75	20.50	19.38
Medium	22.50	22.50	19.75	21.75	20.50	22.50	21.58
Low	21.00	20.25	21.25	23.75	25.75	25.25	22.88

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.7516	---
MZ	0.0099	1.87
Rate x MZ	0.6101	---

Table A1.22. Site year 3 (ARDEC 2005) GNDVI, SPAD and plant height across N application rate and maize growth stage (GS).

GNDVI

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	GNDVI						
Rate Average	0.522	0.543	0.528	0.536	0.532	0.523	
GS							**GS Avg.**
V8	0.420	0.449	0.387	0.422	0.397	0.401	0.413
V12	0.474	0.472	0.488	0.485	0.503	0.485	0.485
V16	0.725	0.709	0.708	0.702	0.698	0.652	0.695

Analysis of Variance	P > F	$LSD_{0.10}$
GS	<0.0001	0.192
N Rate	0.8497	---
Stage * Rate	0.9096	---

SPAD

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	SPAD						
Rate Average	41.9	42.1	42.2	42.1	42.6	42.0	
GS							**GS Avg.**
V8	41.1	41.4	40.7	41.5	40.7	40.1	40.9
V12	41.5	41.5	41.6	41.1	43.0	41.7	41.7
V16	43.8	43.5	44.4	43.8	44.0	43.7	43.8

Analysis of Variance	P > F	$LSD_{0.10}$
GS	0.0321	1.8
N Rate	0.9987	---
Stage * Rate	0.9999	---

Plant Height

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	Height (cm)						
Rate Average	96.4	107.4	106.4	104.1	106.6	112.7	
GS							**GS Avg.**
V8	44.6	44.8	44.9	44.2	45.7	45.3	44.9
V12	110.6	108.7	108.9	106.7	111.7	109.2	109.2
V16	160.1	168.7	165.3	161.3	162.2	166.9	164.5

Analysis of Variance	P > F	$LSD_{0.10}$
GS	<0.0001	4.0
N Rate	0.9160	
Stage * Rate	0.9846	

Table A1.23. Site year 3 (ARDEC 2005) soil N and maize leaf N concentration across N application rate and maize growth stage (GS).

Soil N Conc.

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	Soil N (mg kg^{-1})						
Rate Average	6.17	11.00	9.28	9.05	11.22	10.05	
GS							**GS Avg.**
V8	4.66	5.33	4.83	5.33	5.08	5.42	5.11
V12	6.38	12.00	8.91	8.58	14.83	11.56	10.67
V16	8.25	15.66	14.08	13.25	13.75	12.00	13.04

Analysis of Variance	**P > F**	**$LSD_{0.10}$**
GS	0.0001	2.71
N Rate	0.4494	---
Stage * Rate	0.9277	---

Plant N Conc.

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	Plant N (mg kg^{-1})						
Rate Average	24.52	28.22	28.61	24.46	24.62	26.41	
GS							**GS Avg.**
V8	18.88	21.82	12.07	12.65	17.61	15.26	16.38
V12	37.13	41.94	53.83	37.83	35.00	39.38	21.28
V16	20.38	20.92	19.91	22.92	21.25	21.82	40.98

Analysis of Variance	**P > F**	**$LSD_{0.10}$**
GS	<0.0001	4.07
N Rate	0.7263	---
Stage * Rate	0.1974	---

Table A1.24. Site year 4 (Lucerne 2005) soil N concentration at maize growth stages V8, V12 and V16 across N application rate and management zone (MZ).

Soil N Conc. (V8)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	Soil N (mg kg^{-1})						
Rate Average	15.08	11.42	12.25	13.91	12.00	12.58	
MZ							**Zone Avg.**
High	10.75	8.75	9.75	9.25	10.50	13.00	10.33
Medium	12.00	10.25	10.75	10.00	10.50	9.25	10.45
Low	22.50	15.25	16.25	22.50	15.00	15.50	17.83

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.3738	---
MZ	<0.0001	2.19
Rate x MZ	0.4151	---

Soil N Conc. (V12)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	Soil N (mg kg^{-1})						
Rate Average	18.92	20.33	25.92	24.25	30.08	24.58	
MZ							**Zone Avg.**
High	11.25	19.00	25.50	33.50	37.00	21.50	24.63
Medium	24.75	23.25	25.00	12.25	13.75	13.00	18.67
Low	20.75	18.75	27.25	27.00	39.50	39.25	28.75

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.5008	---
MZ	0.0692	7.16
Rate x MZ	0.1797	---

Soil N Conc. (V16)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	Soil N (mg kg^{-1})						
Rate Average	9.58	9.91	9.75	9.75	10.00	9.58	
MZ							**Zone Avg.**
High	10.00	10.50	10.00	9.25	9.50	9.25	9.75
Medium	9.75	9.00	9.25	10.25	10.75	8.75	9.63
Low	9.00	10.25	10.00	9.75	9.75	10.75	9.91

Analysis of Variance	P > F	$LSD_{0.10}$
Rate	0.9168	---
MZ	0.6540	---
Rate x MZ	0.0785	0.45

Table A1.25. Site year 4 (Lucerne 2005) plant N concentration at maize growth stages V8, V12 and V16 across N rate and management zone (MZ).

Plant N Conc. (V8)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	Plant N (mg kg^{-1})						
Rate Average	43.25	62.00	44.50	40.41	64.83	50.92	
MZ							**Zone Avg.**
High	31.50	71.25	40.00	40.00	110.00	54.75	57.92
Medium	43.50	41.75	32.50	25.25	35.25	48.00	37.71
Low	54.75	73.00	61.00	56.00	49.25	50.00	57.33

Analysis of Variance	**P > F**	**$LSD_{0.10}$**
Rate	0.2212	---
MZ	0.0329	14.3
Rate x MZ	0.1458	---

Plant N Conc. (V12)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	Plant N (mg kg^{-1})						
Rate Average	64.40	63.66	77.66	60.58	57.91	58.91	
MZ							**Zone Avg.**
High	51.75	50.75	59.00	59.50	54.00	56.00	55.16
Medium	48.50	55.00	50.25	48.50	51.00	53.00	51.04
Low	93.00	85.25	123.75	73.75	72.33	67.75	86.56

Analysis of Variance	**P > F**	**$LSD_{0.10}$**
Rate	0.5336	---
MZ	<0.0001	12.9
Rate x MZ	0.6003	---

Plant N Conc. (V16)

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	Plant N (mg kg^{-1})						
Rate Average	16.67	11.75	18.33	19.90	19.17	22.25	
MZ							**Zone Avg.**
High	5.50	6.25	10.75	8.50	15.00	21.25	11.21
Medium	14.00	10.25	19.50	18.75	12.75	14.00	14.88
Low	30.50	18.75	24.75	36.66	29.75	31.50	28.30

Analysis of Variance	**P > F**	**$LSD_{0.10}$**
Rate	0.5808	---
MZ	0.0005	7.09
Rate x MZ	0.9476	---

Table A1.26. Site year 4 (Lucerne 2005) GNDVI, SPAD and plant height across N application rate and maize growth stage (GS).

GNDVI

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	----------GNDVI----------						
Rate Average	0.565	0.567	0.564	0.571	0.573	0.566	
GS							**GS Avg.**
V8	0.422	0.421	0.430	0.419	0.415	0.432	0.423
V12	0.564	0.562	0.569	0.555	0.560	0.554	0.561
V16	0.709	0.718	0.694	0.741	0.743	0.714	0.720

Analysis of Variance	P > F	$LSD_{0.10}$
GS	<0.0001	0.010
N Rate	0.8535	---
Stage * Rate	0.0522	0.009

SPAD

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	----------SPAD----------						
Rate Average	50.0	49.7	49.9	50.1	50.9	50.0	
GS							**GS Avg.**
V8	46.7	45.7	45.4	45.6	46.9	45.6	46.0
V12	50.4	50.6	50.5	50.7	51.0	50.4	50.6
V16	53.8	52.8	53.9	53.9	54.7	54.0	53.7

Analysis of Variance	P > F	$LSD_{0.10}$
GS	<0.0001	1.1
N Rate	0.8771	---
Stage * Rate	0.9944	---

Plant Height

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	----------Height (cm)----------						
Rate Average	127.1	121.3	120.0	117.8	112.5	118.3	
GS							**GS Avg.**
V8	64.0	65.5	63.4	62.6	64.1	63.2	63.7
V12	145.3	123.2	123.0	121.6	121.4	120.0	125.7
V16	171.6	176.3	173.7	169.2	171.9	171.7	172.5

Analysis of Variance	P > F	$LSD_{0.10}$
GS	<0.0001	6.5
N Rate	0.5752	---
Stage * Rate	0.6937	---

Table A1.27. Site year 4 (Lucerne 2005) soil N and maize leaf N concentration across N application rate and maize growth stage (GS).

Soil N Conc.

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	---Soil N (mg kg^{-1})---						
Rate Average	16.89	14.50	18.83	19.82	20.42	19.81	
GS							**GS Avg.**
V8	15.08	11.41	12.25	13.92	12.00	12.58	12.86
V12	18.92	20.33	25.91	24.25	30.08	24.58	24.01
V16	16.67	11.75	18.33	21.31	19.17	22.25	18.25

Analysis of Variance	P > F	$LSD_{0.10}$
GS	0.0017	4.80
N Rate	0.6734	---
Stage * Rate	0.9624	---

Plant N Conc.

	N rate (kg ha^{-1})						
	0	50	100	150	200	250	
	---Plant N (mg kg^{-1})---						
Rate Average	52.17	57.86	56.31	50.31	57.68	54.53	
GS							**GS Avg.**
V8	43.25	62.00	44.50	40.42	64.83	50.92	50.99
V12	64.42	63.67	77.66	60.58	59.11	58.92	64.06
V16	48.83	47.91	46.75	49.94	49.08	53.75	49.38

Analysis of Variance	P > F	$LSD_{0.10}$
GS	0.0456	10.48
N Rate	0.9399	---
Stage * Rate	0.8240	---

Table A1.28. Average GNDVI, SPAD and Plant Height in the high, medium and low production level management zones (MZ) at the V8, V12 and V16 maize growth stages at Lucerne in 2005.

GNDVI

MZ	Lucerne V8	Lucerne V12	Lucerne V16
	---GNDVI---		
High	0.410 a	0.564	0.728
Medium	0.430 b	0.562	0.718
Low	0.429 b	0.552	0.713

*Different letters indicate significant differences at alpha = 0.10.
No letters indicate no significant differences.

SPAD

MZ	Lucerne V8	Lucerne V12	Lucerne V16
	---SPAD---		
High	46.1 ab	52.9 a	54.9 a
Medium	45.3 b	50.0 b	53.9 a
Low	46.6 a	48.8 c	52.2 b

*Different letters indicate significant differences at alpha = 0.10.
No letters indicate no significant differences.

Plant Height

MZ	Lucerne V8	Lucerne V12	Lucerne V16
	---cm---		
High	64 ab	135	175 a
Medium	65 a	127	179 a
Low	62 b	116	164 b

*Different letters indicate significant differences at alpha = 0.10.
No letters indicate no significant differences.

APPENDIX B

Table A2.1. Greenhouse amber NDVI as affected by corn growth stage and N rate at 25 cm row spacing.

	Corn Growth Stage				
	V8	V9	V10	V11	V12
N Rate (kg ha^{-1})	Amber NDVI				
0	0.421	0.466	0.456	0.445	0.476
	0.452	0.450	0.476	0.424	0.459
	0.467	0.447	0.457	0.398	0.487
	0.415	0.427	0.463	0.385	0.435
	0.430	0.454	0.455	0.458	0.368
	0.481	0.449	0.474	0.489	0.484
	0.416	0.437	0.443	0.463	0.435
	0.460	0.477	0.464	0.395	0.489
	0.521	0.467	0.460	0.448	0.393
	0.458	0.487	0.407	0.355	0.490
	0.459	0.455	0.453	0.437	0.490
	0.465	0.445	0.447	0.443	0.396
	0.488	0.448	0.496	0.447	0.393
	0.496	0.452	0.466	0.448	0.491
	0.452	0.424	0.466	0.446	0.463
	0.446	0.449	0.487	0.435	0.449
	0.437	0.456	0.457	0.448	0.489
	0.452	0.497	0.455	0.464	0.448
	0.494	0.442	0.478	0.431	0.488
	0.446	0.479	0.476	0.392	0.433
75	0.467	0.491	0.614	0.652	0.710
	0.463	0.499	0.606	0.680	0.681
	0.468	0.467	0.617	0.705	0.687
	0.435	0.490	0.638	0.674	0.653
	0.452	0.486	0.640	0.644	0.701
	0.514	0.555	0.559	0.646	0.685
	0.445	0.503	0.594	0.677	0.703
	0.448	0.482	0.645	0.672	0.699
	0.493	0.512	0.611	0.656	0.675
	0.489	0.509	0.675	0.639	0.706
	0.448	0.492	0.563	0.665	0.684
	0.512	0.422	0.611	0.657	0.689
	0.411	0.577	0.628	0.649	0.704
	0.514	0.523	0.616	0.652	0.705
	0.451	0.444	0.624	0.653	0.706
	0.517	0.448	0.627	0.652	0.688
	0.443	0.488	0.626	0.649	0.687
	0.500	0.499	0.617	0.651	0.699
	0.480	0.418	0.636	0.687	0.715
	0.500	0.496	0.637	0.674	0.688

	Corn Growth Stage				
	V8	**V9**	**V10**	**V11**	**V12**
N Rate (kg ha^{-1})	------	------	**Amber NDVI**	------	------
150	0.522	0.564	0.664	0.745	0.754
	0.522	0.549	0.689	0.731	0.743
	0.489	0.586	0.732	0.728	0.762
	0.566	0.543	0.661	0.729	0.720
	0.526	0.585	0.666	0.719	0.720
	0.526	0.521	0.585	0.668	0.743
	0.477	0.533	0.703	0.712	0.762
	0.562	0.566	0.657	0.657	0.763
	0.521	0.565	0.679	0.721	0.751
	0.489	0.587	0.679	0.728	0.754
	0.489	0.561	0.675	0.716	0.762
	0.563	0.583	0.663	0.728	0.746
	0.576	0.571	0.663	0.706	0.762
	0.576	0.569	0.648	0.714	0.763
	0.564	0.572	0.665	0.729	0.744
	0.567	0.566	0.678	0.676	0.763
	0.543	0.569	0.679	0.706	0.767
	0.475	0.557	0.690	0.704	0.664
	0.568	0.584	0.667	0.716	0.752
	0.559	0.541	0.693	0.659	0.723
225	0.571	0.676	0.704	0.679	0.728
	0.547	0.661	0.676	0.719	0.719
	0.617	0.671	0.662	0.722	0.740
	0.554	0.673	0.665	0.699	0.732
	0.580	0.681	0.704	0.713	0.727
	0.573	0.659	0.652	0.715	0.702
	0.560	0.552	0.634	0.726	0.728
	0.576	0.671	0.684	0.671	0.727
	0.579	0.678	0.710	0.718	0.759
	0.569	0.666	0.589	0.616	0.728
	0.574	0.667	0.645	0.725	0.729
	0.576	0.660	0.684	0.711	0.720
	0.571	0.515	0.662	0.714	0.732
	0.572	0.659	0.685	0.703	0.734
	0.579	0.562	0.600	0.723	0.736
	0.583	0.588	0.708	0.722	0.729
	0.616	0.562	0.707	0.711	0.728
	0.578	0.660	0.683	0.723	0.728
	0.573	0.592	0.702	0.727	0.738
	0.571	0.667	0.697	0.717	0.723

Table A2.2. Greenhouse amber NDVI as affected by corn growth stage and N rate at 50 cm row spacing.

	Corn Growth Stage				
	V8	V9	V10	V11	V12
N Rate (kg ha^{-1})	----------	----------	Amber NDVI	----------	----------
0	0.316	0.276	0.353	0.305	0.385
	0.283	0.289	0.372	0.312	0.384
	0.320	0.262	0.297	0.302	0.355
	0.423	0.305	0.404	0.313	0.380
	0.307	0.301	0.472	0.374	0.384
	0.314	0.302	0.384	0.310	0.376
	0.319	0.298	0.402	0.288	0.387
	0.315	0.316	0.363	0.304	0.386
	0.285	0.296	0.372	0.332	0.354
	0.360	0.283	0.322	0.349	0.385
	0.287	0.299	0.371	0.302	0.412
	0.307	0.276	0.321	0.342	0.387
	0.283	0.278	0.357	0.303	0.347
	0.305	0.295	0.362	0.302	0.384
	0.312	0.402	0.366	0.332	0.377
	0.291	0.344	0.373	0.369	0.384
	0.394	0.303	0.319	0.288	0.374
	0.311	0.280	0.384	0.305	0.385
	0.309	0.283	0.338	0.333	0.384
	0.268	0.308	0.367	0.408	0.387
75	0.302	0.299	0.493	0.615	0.625
	0.335	0.290	0.424	0.627	0.639
	0.342	0.350	0.498	0.617	0.623
	0.314	0.302	0.440	0.600	0.637
	0.386	0.281	0.466	0.575	0.635
	0.322	0.278	0.482	0.626	0.635
	0.301	0.348	0.506	0.589	0.637
	0.333	0.277	0.463	0.618	0.568
	0.328	0.272	0.447	0.618	0.590
	0.364	0.330	0.455	0.629	0.636
	0.401	0.274	0.533	0.579	0.651
	0.322	0.322	0.562	0.600	0.625
	0.325	0.270	0.380	0.507	0.634
	0.313	0.278	0.389	0.519	0.638
	0.367	0.284	0.453	0.625	0.634
	0.388	0.278	0.498	0.613	0.637
	0.313	0.264	0.565	0.615	0.636
	0.453	0.279	0.497	0.581	0.640
	0.334	0.266	0.520	0.621	0.591
	0.343	0.243	0.561	0.618	0.628

			Corn Growth Stage		
	V8	**V9**	**V10**	**V11**	**V12**
N Rate (kg ha^{-1})	----------------	----------------	**Amber NDVI**	----------------	----------------
150	0.309	0.397	0.546	0.659	0.703
	0.315	0.431	0.551	0.603	0.705
	0.368	0.385	0.481	0.603	0.703
	0.338	0.410	0.563	0.602	0.709
	0.329	0.386	0.532	0.602	0.717
	0.435	0.384	0.542	0.642	0.703
	0.393	0.372	0.541	0.548	0.709
	0.329	0.402	0.554	0.569	0.709
	0.345	0.381	0.554	0.588	0.710
	0.323	0.388	0.565	0.518	0.715
	0.319	0.506	0.449	0.599	0.709
	0.327	0.374	0.483	0.528	0.604
	0.444	0.414	0.575	0.600	0.709
	0.311	0.373	0.565	0.628	0.709
	0.384	0.385	0.465	0.646	0.722
	0.355	0.401	0.500	0.598	0.640
	0.351	0.409	0.550	0.605	0.683
	0.376	0.397	0.567	0.641	0.645
	0.336	0.427	0.514	0.537	0.677
	0.321	0.388	0.536	0.605	0.709
225	0.452	0.594	0.630	0.640	0.695
	0.452	0.540	0.628	0.636	0.671
	0.422	0.469	0.582	0.685	0.670
	0.472	0.508	0.637	0.665	0.646
	0.472	0.444	0.627	0.659	0.704
	0.505	0.499	0.619	0.682	0.728
	0.455	0.252	0.628	0.659	0.670
	0.466	0.527	0.615	0.572	0.670
	0.466	0.463	0.635	0.672	0.684
	0.403	0.533	0.618	0.634	0.697
	0.416	0.540	0.624	0.635	0.670
	0.388	0.459	0.588	0.672	0.659
	0.475	0.473	0.588	0.486	0.670
	0.418	0.469	0.613	0.642	0.716
	0.455	0.492	0.630	0.664	0.708
	0.510	0.456	0.615	0.659	0.703
	0.387	0.471	0.594	0.710	0.701
	0.469	0.450	0.616	0.669	0.654
	0.362	0.527	0.616	0.681	0.693
	0.412	0.472	0.580	0.663	0.670

Table A2.3. Greenhouse amber NDVI as affected by corn growth stage and N rate at 75 cm row spacing.

	Corn Growth Stage				
	V8	V9	V10	V11	V12
N Rate (kg ha^{-1})	----------	----------	Amber NDVI	----------	----------
0	0.263	0.255	0.385	0.298	0.339
	0.300	0.231	0.450	0.268	0.320
	0.289	0.257	0.326	0.288	0.344
	0.283	0.230	0.321	0.374	0.269
	0.384	0.249	0.343	0.293	0.339
	0.247	0.250	0.328	0.342	0.375
	0.248	0.269	0.386	0.310	0.335
	0.278	0.255	0.348	0.276	0.338
	0.259	0.323	0.406	0.272	0.274
	0.242	0.237	0.375	0.272	0.342
	0.291	0.233	0.334	0.267	0.378
	0.282	0.280	0.378	0.270	0.340
	0.248	0.355	0.334	0.302	0.363
	0.255	0.341	0.346	0.293	0.341
	0.258	0.232	0.348	0.282	0.291
	0.300	0.383	0.247	0.338	0.352
	0.405	0.250	0.365	0.273	0.343
	0.377	0.227	0.334	0.361	0.342
	0.258	0.255	0.369	0.308	0.333
	0.278	0.300	0.349	0.296	0.338
75	0.302	0.279	0.452	0.627	0.615
	0.239	0.388	0.436	0.527	0.610
	0.348	0.329	0.456	0.457	0.623
	0.311	0.401	0.416	0.666	0.633
	0.312	0.289	0.381	0.644	0.646
	0.308	0.316	0.466	0.602	0.623
	0.393	0.251	0.427	0.558	0.625
	0.289	0.264	0.518	0.636	0.615
	0.389	0.307	0.445	0.527	0.620
	0.312	0.279	0.419	0.567	0.653
	0.383	0.324	0.426	0.520	0.628
	0.326	0.376	0.391	0.636	0.625
	0.312	0.311	0.460	0.637	0.642
	0.329	0.293	0.383	0.654	0.623
	0.311	0.288	0.484	0.603	0.624
	0.310	0.318	0.424	0.642	0.622
	0.313	0.279	0.383	0.606	0.640
	0.314	0.293	0.473	0.606	0.642
	0.314	0.401	0.458	0.608	0.623
	0.320	0.281	0.451	0.594	0.623

	Corn Growth Stage				
	V8	V9	V10	V11	V12
N Rate (kg ha^{-1})	Amber NDVI				
150	0.314	0.376	0.527	0.552	0.675
	0.307	0.353	0.529	0.559	0.687
	0.325	0.377	0.545	0.576	0.686
	0.311	0.300	0.533	0.565	0.681
	0.329	0.475	0.573	0.567	0.698
	0.338	0.386	0.581	0.464	0.675
	0.308	0.453	0.542	0.550	0.686
	0.312	0.379	0.529	0.560	0.712
	0.304	0.367	0.524	0.447	0.705
	0.388	0.470	0.502	0.555	0.714
	0.300	0.470	0.528	0.638	0.662
	0.325	0.420	0.592	0.537	0.709
	0.430	0.385	0.552	0.571	0.682
	0.431	0.356	0.566	0.573	0.686
	0.325	0.376	0.531	0.548	0.714
	0.338	0.442	0.533	0.565	0.686
	0.331	0.377	0.601	0.566	0.720
	0.341	0.353	0.523	0.566	0.662
	0.305	0.453	0.557	0.581	0.704
	0.323	0.367	0.533	0.601	0.700
225	0.476	0.528	0.571	0.629	0.662
	0.446	0.428	0.547	0.706	0.667
	0.436	0.458	0.588	0.635	0.668
	0.453	0.477	0.571	0.650	0.647
	0.455	0.506	0.567	0.483	0.721
	0.479	0.478	0.575	0.560	0.707
	0.444	0.555	0.576	0.664	0.662
	0.471	0.478	0.566	0.631	0.663
	0.470	0.393	0.562	0.621	0.669
	0.419	0.476	0.604	0.637	0.666
	0.417	0.481	0.569	0.632	0.713
	0.468	0.478	0.577	0.651	0.669
	0.463	0.519	0.593	0.627	0.667
	0.421	0.573	0.595	0.640	0.725
	0.326	0.421	0.579	0.701	0.704
	0.468	0.485	0.570	0.629	0.627
	0.429	0.479	0.583	0.658	0.673
	0.451	0.482	0.540	0.632	0.711
	0.446	0.503	0.571	0.629	0.660
	0.455	0.477	0.580	0.623	0.706

Table A2.4. Greenhouse red NDVI as affected by corn growth stage and N rate at 25 cm row spacing.

	Corn Growth Stage				
	V8	**V9**	**V10**	**V11**	**V12**
N Rate (kg ha^{-1})	----------------------	----------------------	**Red NDVI**	----------------------	----------------------
0	0.720	0.510	0.620	0.490	0.565
	0.595	0.180	0.545	0.485	0.685
	0.440	0.540	0.580	0.675	0.650
	0.570	0.160	0.630	0.545	0.540
	0.535	0.515	0.540	0.615	0.585
	0.640	0.520	0.625	0.620	0.590
	0.620	0.515	0.570	0.660	0.615
	0.720	0.490	0.625	0.520	0.675
	0.555	0.505	0.535	0.505	0.525
	0.700	0.505	0.540	0.485	0.660
	0.685	0.510	0.615	0.505	0.710
	0.590	0.495	0.585	0.385	0.595
	0.625	0.525	0.565	0.510	0.560
	0.580	0.505	0.750	0.670	0.610
	0.605	0.555	0.565	0.485	0.610
	0.655	0.525	0.590	0.530	0.650
	0.730	0.280	0.545	0.540	0.690
	0.540	0.570	0.525	0.550	0.590
	0.725	0.500	0.735	0.680	0.585
	0.680	0.485	0.585	0.540	0.615
75	0.545	0.620	0.745	0.790	0.865
	0.495	0.640	0.730	0.805	0.865
	0.315	0.635	0.745	0.785	0.865
	0.530	0.660	0.735	0.790	0.885
	0.410	0.625	0.800	0.790	0.850
	0.495	0.590	0.760	0.805	0.885
	0.520	0.630	0.755	0.820	0.885
	0.425	0.650	0.750	0.805	0.890
	0.575	0.520	0.745	0.770	0.890
	0.435	0.675	0.745	0.795	0.885
	0.490	0.670	0.740	0.820	0.855
	0.655	0.635	0.740	0.775	0.890
	0.545	0.615	0.730	0.795	0.895
	0.505	0.630	0.785	0.810	0.885
	0.310	0.655	0.630	0.795	0.880
	0.320	0.630	0.755	0.815	0.855
	0.630	0.780	0.730	0.780	0.885
	0.610	0.640	0.795	0.775	0.885
	0.405	0.690	0.750	0.775	0.885
	0.510	0.645	0.735	0.785	0.880

	Corn Growth Stage				
	V8	V9	V10	V11	V12
N Rate (kg ha^{-1})	----------------------------------		Amber NDVI	----------------------------------	
150	0.655	0.735	0.805	0.870	0.915
	0.620	0.795	0.835	0.850	0.900
	0.515	0.795	0.815	0.870	0.905
	0.630	0.730	0.820	0.885	0.925
	0.540	0.710	0.820	0.870	0.925
	0.630	0.645	0.805	0.845	0.925
	0.650	0.740	0.835	0.880	0.935
	0.540	0.760	0.820	0.860	0.925
	0.615	0.740	0.820	0.860	0.925
	0.635	0.760	0.825	0.865	0.910
	0.515	0.675	0.770	0.855	0.920
	0.645	0.640	0.820	0.835	0.935
	0.560	0.740	0.835	0.845	0.910
	0.650	0.750	0.815	0.845	0.925
	0.630	0.735	0.755	0.880	0.925
	0.655	0.665	0.820	0.850	0.930
	0.570	0.735	0.815	0.860	0.915
	0.705	0.680	0.755	0.845	0.930
	0.670	0.805	0.825	0.865	0.925
	0.515	0.730	0.860	0.875	0.930
225	0.675	.	0.795	0.870	0.900
	0.685	.	0.835	0.800	0.905
	0.765	.	0.845	0.555	0.925
	0.650	.	0.810	0.865	0.885
	0.760	.	0.850	0.860	0.940
	0.750	.	0.835	0.805	0.900
	0.740	.	0.835	0.815	0.920
	0.655	.	0.850	0.850	0.930
	0.655	.	0.840	0.815	0.910
	0.665	.	0.785	0.800	0.935
	0.760	.	0.815	0.825	0.920
	0.660	.	0.850	0.860	0.890
	0.670	.	0.845	0.820	0.895
	0.730	.	0.845	0.875	0.920
	0.665	.	0.825	0.820	0.905
	0.745	.	0.850	0.855	0.900
	0.640	.	0.820	0.830	0.910
	0.735	.	0.835	0.855	0.925
	0.675	.	0.835	0.825	0.925
	0.670	.	0.830	0.860	0.905

Table A2.5. Greenhouse red NDVI as affected by corn growth stage and N rate at 50 cm row spacing.

	Corn Growth Stage				
	V8	V9	V10	V11	V12
N Rate (kg ha^{-1})			Red NDVI		
0	0.285	0.360	0.415	0.435	0.550
	0.320	0.325	0.415	0.465	0.415
	0.330	0.350	0.285	0.465	0.490
	0.355	0.370	0.410	0.410	0.520
	0.390	0.395	0.395	0.435	0.585
	0.325	0.315	0.450	0.495	0.500
	0.370	0.370	0.435	0.480	0.485
	0.360	0.365	0.435	0.430	0.560
	0.410	0.360	0.455	0.465	0.625
	0.400	0.330	0.445	0.385	0.630
	0.275	0.395	0.465	0.430	0.490
	0.335	0.330	0.455	0.425	0.260
	0.335	0.365	0.615	0.485	0.520
	0.415	0.360	0.425	0.530	0.395
	0.360	0.380	0.480	0.490	0.620
	0.265	0.350	0.400	0.500	0.505
	0.380	0.345	0.455	0.445	0.395
	0.340	0.305	0.515	0.445	0.285
	0.410	0.380	0.460	0.400	0.420
	0.275	0.355	0.265	0.450	0.490
75	0.300	0.480	0.505	0.775	0.765
	0.280	0.495	0.525	0.775	0.775
	0.390	0.515	0.520	0.720	0.840
	0.295	0.310	0.545	0.695	0.850
	0.160	0.415	0.540	0.675	0.790
	0.355	0.320	0.600	0.770	0.820
	0.290	0.390	0.720	0.805	0.845
	0.370	0.725	0.535	0.760	0.845
	0.545	0.455	0.550	0.735	0.845
	0.285	0.395	0.530	0.745	0.840
	0.480	0.370	0.525	0.760	0.860
	0.355	0.380	0.665	0.680	0.860
	0.305	0.565	0.545	0.735	0.855
	0.355	0.460	0.510	0.770	0.840
	0.290	0.335	0.495	0.700	0.840
	0.390	0.725	0.465	0.750	0.800
	0.305	0.515	0.540	0.615	0.845
	0.285	0.530	0.525	0.770	0.835
	0.315	0.735	0.510	0.675	0.820
	0.295	0.435	.	0.765	0.840

	Corn Growth Stage				
	V8	V9	V10	V11	V12
N Rate (kg ha^{-1})			Amber NDVI		
150	0.390	0.385	0.785	0.775	0.915
	0.470	0.390	0.795	0.775	0.845
	0.470	0.600	0.765	0.805	0.925
	0.485	0.400	0.845	0.850	0.890
	0.440	0.400	0.805	0.810	0.895
	0.470	0.375	0.650	0.805	0.885
	0.510	0.390	0.795	0.805	0.930
	0.450	0.390	0.800	0.835	0.845
	0.330	0.380	0.735	0.770	0.900
	0.465	0.360	0.790	0.765	0.830
	0.550	0.380	0.840	0.775	0.895
	0.435	0.385	0.715	0.830	0.895
	0.440	0.385	0.640	0.755	0.865
	0.460	0.420	0.780	0.800	0.835
	0.530	0.605	0.820	0.780	0.930
	0.365	0.585	0.780	0.800	0.930
	0.440	0.380	0.735	0.820	0.825
	0.370	0.385	0.795	0.780	0.890
	0.495	0.385	0.770	0.825	0.835
	0.450	0.390	0.795	0.755	0.895
225	0.325	0.575	0.765	0.720	0.925
	0.540	0.750	0.780	0.630	0.880
	0.335	0.830	0.755	0.725	0.930
	0.510	0.770	0.785	0.840	0.875
	0.685	0.770	0.820	0.785	0.925
	0.650	0.690	0.815	0.750	0.870
	0.465	0.685	0.780	0.830	0.920
	0.525	0.765	0.805	0.775	0.890
	0.515	0.660	0.780	0.750	0.905
	0.485	0.765	0.815	0.750	0.925
	0.370	0.705	0.790	0.735	0.895
	0.385	0.575	0.765	0.830	0.870
	0.515	0.725	0.795	0.785	0.870
	0.380	0.745	0.775	0.750	0.915
	0.500	0.745	0.780	0.845	0.915
	0.360	0.765	0.360	0.775	0.875
	0.380	0.785	0.795	0.745	0.875
	0.605	0.740	0.810	0.750	0.920
	0.325	0.750	0.765	0.790	0.825
	0.530	0.695	0.810	0.740	0.900

Table A2.6. Greenhouse red NDVI as affected by corn growth stage and N rate at 75 cm row spacing.

	Corn Growth Stage				
	V8	V9	V10	V11	V12
N Rate (kg ha^{-1})			Red NDVI		
0	0.285	0.330	0.440	0.370	0.525
	0.320	0.340	0.515	0.405	0.520
	0.325	0.345	0.365	0.395	0.450
	0.380	0.265	0.445	0.400	0.535
	0.395	0.330	0.425	0.480	0.470
	0.365	0.300	0.425	0.475	0.380
	0.315	0.275	0.510	0.440	0.470
	0.375	0.360	0.485	0.370	0.545
	0.300	0.300	0.425	0.410	0.375
	0.230	0.425	0.500	0.540	0.385
	0.220	0.260	0.380	0.405	0.390
	0.405	0.295	0.445	0.435	0.380
	0.370	0.315	0.445	0.385	0.215
	0.470	0.315	0.435	0.435	0.475
	0.295	0.355	0.415	0.375	0.215
	0.445	0.300	0.425	0.385	0.435
	0.325	0.125	0.435	0.420	0.435
	0.400	0.305	0.380	0.360	0.400
	0.335	0.300	0.425	0.390	0.525
	0.400	0.310	0.545	0.370	0.475
75	0.350	0.370	0.430	0.670	0.850
	0.355	0.285	0.630	0.555	0.810
	0.330	0.335	0.605	0.620	0.810
	0.310	0.345	0.635	0.480	0.830
	0.325	0.260	0.625	0.525	0.795
	0.325	0.405	0.670	0.560	0.795
	0.325	0.240	0.585	0.460	0.820
	0.350	0.260	0.625	0.770	0.800
	0.365	0.360	0.660	0.770	0.805
	0.335	0.270	0.615	0.605	0.845
	0.425	0.355	0.605	0.460	0.835
	0.395	0.270	0.630	0.580	0.755
	0.345	0.355	0.430	0.625	0.815
	0.335	0.270	0.670	0.465	0.810
	0.325	0.300	0.470	0.590	0.815
	0.345	0.325	0.560	0.770	0.840
	0.365	0.345	0.600	0.525	0.850
	0.290	0.475	0.655	0.640	0.820
	0.365	0.325	0.655	0.655	0.825
	0.330	0.435	0.640	0.640	0.830

	Corn Growth Stage				
	V8	V9	V10	V11	V12
N Rate (kg ha^{-1})	------------------	------------------	Amber NDVI	------------------	------------------
150	0.530	0.360	0.785	0.770	0.915
	0.255	0.505	0.735	0.815	0.905
	0.350	0.300	0.655	0.815	0.915
	0.320	0.480	0.775	0.810	0.905
	0.340	0.265	0.720	0.640	0.920
	0.295	0.490	0.715	0.760	0.905
	0.485	0.305	0.745	0.815	0.875
	0.590	0.320	0.595	0.750	0.890
	0.310	0.530	0.685	0.805	0.925
	0.525	0.350	0.610	0.545	0.865
	0.295	0.310	0.685	0.545	0.910
	0.325	0.320	0.760	0.770	0.900
	0.330	0.340	0.765	0.810	0.875
	0.360	0.300	0.745	0.820	0.910
	0.485	0.335	0.710	0.815	0.870
	0.430	0.415	0.715	0.830	0.900
	0.395	0.280	0.715	0.790	0.900
	0.330	0.550	0.530	0.820	0.930
	0.330	0.470	0.750	0.845	0.890
	0.470	0.345	0.735	0.745	0.910
225	0.785	0.755	0.765	0.850	0.915
	0.660	0.750	0.800	0.785	0.890
	0.510	0.680	0.795	0.780	0.810
	0.525	0.635	0.825	0.770	0.800
	0.420	0.745	0.825	0.725	0.865
	0.380	0.760	0.805	0.765	0.800
	0.535	0.650	0.785	0.725	0.900
	0.475	0.730	0.835	0.785	0.870
	0.800	0.760	0.825	0.760	0.910
	0.530	0.750	0.750	0.690	0.910
	0.520	0.755	0.825	0.880	0.830
	0.800	0.585	0.800	0.790	0.865
	0.495	0.650	0.785	0.790	0.795
	0.425	0.635	0.815	0.785	0.780
	0.680	0.665	0.810	0.790	0.875
	0.470	0.540	0.815	0.785	0.910
	0.585	0.590	0.785	0.790	0.865
	0.485	0.780	0.795	0.725	0.800
	0.540	0.830	0.785	0.785	0.865
	0.550	0.730	0.805	0.850	0.810

Table A2.7. Greenhouse green NDVI as affected by corn growth stage and N rate at 25 cm row spacing.

	Corn Growth Stage				
	V8	V9	V10	V11	V12
N Rate (kg ha^{-1})	----------	----------	Green NDVI	----------	----------
0	0.533	0.407	0.390	0.340	0.437
	0.517	0.400	0.360	0.350	0.437
	0.520	0.367	0.367	0.347	0.460
	0.527	0.347	0.363	0.330	0.440
	0.530	0.330	0.373	0.320	0.433
	0.550	0.350	0.347	0.333	0.413
	0.540	0.407	0.343	0.347	0.440
	0.530	0.427	0.350	0.357	0.463
	0.497	0.423	0.353	0.353	0.447
	0.500	0.383	0.370	0.363	0.443
	0.503	0.413	0.367	0.357	0.433
	0.493	0.433	0.383	0.350	0.443
	0.467	0.453	0.393	0.350	0.457
	0.480	0.423	0.403	0.343	0.437
	0.473	0.410	0.400	0.347	0.450
	0.480	0.387	0.377	0.340	0.427
	0.470	0.377	0.367	0.347	0.407
	0.503	0.383	0.337	0.353	0.377
	0.517	0.407	0.343	0.373	0.377
	0.507	0.393	0.347	0.373	0.380
75	0.467	0.363	0.473	0.613	0.733
	0.457	0.357	0.463	0.603	0.730
	0.457	0.363	0.440	0.603	0.730
	0.450	0.383	0.463	0.600	0.733
	0.460	0.383	0.470	0.603	0.747
	0.483	0.377	0.477	0.607	0.743
	0.493	0.333	0.460	0.607	0.737
	0.487	0.310	0.450	0.600	0.727
	0.467	0.320	0.450	0.603	0.733
	0.450	0.333	0.457	0.607	0.747
	0.443	0.343	0.493	0.620	0.747
	0.450	0.360	0.500	0.617	0.743
	0.480	0.340	0.493	0.613	0.733
	0.493	0.313	0.467	0.597	0.737
	0.503	0.303	0.457	0.593	0.737
	0.460	0.300	0.447	0.593	0.743
	0.430	0.333	0.443	0.603	0.750
	0.427	0.313	0.443	0.610	0.750
	0.453	0.353	0.457	0.610	0.743
	0.500	0.347	0.460	0.603	0.737

	Corn Growth Stage				
	V8	V9	V10	V11	V12
N Rate (kg ha^{-1})	----------	----------	Amber NDVI	----------	----------
150	0.543	0.603	0.590	0.633	0.837
	0.537	0.603	0.610	0.637	0.840
	0.540	0.587	0.620	0.643	0.837
	0.540	0.587	0.623	0.640	0.840
	0.550	0.550	0.603	0.637	0.837
	0.557	0.560	0.600	0.633	0.837
	0.557	0.557	0.587	0.643	0.833
	0.560	0.593	0.610	0.643	0.837
	0.553	0.607	0.607	0.640	0.837
	0.553	0.623	0.623	0.627	0.837
	0.537	0.613	0.610	0.623	0.833
	0.537	0.587	0.620	0.623	0.830
	0.540	0.597	0.607	0.627	0.827
	0.547	0.617	0.610	0.623	0.830
	0.527	0.630	0.607	0.623	0.830
	0.530	0.613	0.610	0.633	0.827
	0.523	0.567	0.613	0.633	0.823
	0.537	0.570	0.603	0.633	0.827
	0.523	0.563	0.613	0.623	0.830
	0.550	0.577	0.603	0.633	0.837
225	0.593	0.673	0.657	0.617	0.843
	0.600	0.667	0.660	0.630	0.837
	0.597	0.670	0.663	0.627	0.840
	0.583	0.667	0.667	0.630	0.840
	0.577	0.673	0.663	0.620	0.840
	0.583	0.670	0.660	0.627	0.840
	0.597	0.670	0.650	0.620	0.840
	0.603	0.677	0.650	0.630	0.847
	0.593	0.677	0.650	0.623	0.843
	0.593	0.673	0.653	0.627	0.840
	0.590	0.663	0.653	0.617	0.837
	0.583	0.667	0.653	0.617	0.843
	0.577	0.670	0.650	0.610	0.843
	0.580	0.670	0.657	0.617	0.847
	0.590	0.663	0.660	0.623	0.837
	0.593	0.663	0.660	0.623	0.837
	0.597	0.660	0.650	0.620	0.833
	0.600	0.657	0.640	0.620	0.843
	0.610	0.667	0.637	0.620	0.843
	0.603	0.663	0.643	0.623	0.840

Table A2.8. Greenhouse green NDVI as affected by corn growth stage and N rate at 50 cm row spacing.

	Corn Growth Stage				
	V8	V9	V10	V11	V12
N Rate (kg ha^{-1})	------------	------------	Green NDVI	------------	------------
0	0.423	0.233	0.183	0.220	0.387
	0.427	0.227	0.197	0.220	0.383
	0.423	0.223	0.193	0.230	0.363
	0.427	0.173	0.180	0.230	0.347
	0.420	0.217	0.200	0.210	0.317
	0.397	0.230	0.233	0.213	0.307
	0.400	0.273	0.253	0.223	0.310
	0.403	0.247	0.240	0.243	0.320
	0.423	0.257	0.237	0.227	0.357
	0.423	0.263	0.200	0.247	0.373
	0.423	0.290	0.210	0.237	0.420
	0.423	0.267	0.207	0.240	0.373
	0.423	0.247	0.240	0.220	0.357
	0.417	0.213	0.240	0.220	0.303
	0.413	0.237	0.240	0.230	0.310
	0.417	0.230	0.240	0.250	0.293
	0.410	0.247	0.233	0.253	0.310
	0.417	0.213	0.237	0.243	0.307
	0.413	0.223	0.230	0.227	0.317
	0.417	0.217	0.217	0.213	0.327
75	0.377	0.403	0.310	.	0.590
	0.370	0.407	0.317	.	0.743
	0.353	0.413	0.327	.	0.743
	0.363	0.413	0.327	.	0.750
	0.367	0.407	0.323	.	0.743
	0.387	0.380	0.293	.	0.740
	0.373	0.397	0.300	.	0.730
	0.360	0.407	0.293	.	0.730
	0.347	0.420	0.300	.	0.730
	0.350	0.403	0.287	.	0.730
	0.367	0.393	0.310	.	0.730
	0.383	0.383	0.323	.	0.737
	0.397	0.367	0.343	.	0.740
	0.407	0.347	0.333	.	0.740
	0.383	0.333	0.327	.	0.730
	0.380	0.320	0.327	.	0.730
	0.377	0.333	0.347	.	0.723
	0.387	0.367	0.367	.	0.727
	0.380	0.363	0.363	.	0.730
	0.373	0.347	0.350	.	0.740

	Corn Growth Stage				
	V8	V9	V10	V11	V12
N Rate (kg ha^{-1})	------------------	------------------	Amber NDVI	------------------	------------------
150	0.457	0.310	0.427	0.647	0.717
	0.430	0.287	0.437	0.643	0.700
	0.413	0.280	0.460	0.633	0.703
	0.390	0.253	0.453	0.637	0.707
	0.410	0.267	0.447	0.637	0.723
	0.400	0.277	0.430	0.643	0.733
	0.410	0.307	0.427	0.633	0.737
	0.397	0.343	0.413	0.640	0.720
	0.407	0.360	0.417	0.640	0.707
	0.413	0.380	0.403	0.640	0.710
	0.430	0.337	0.430	0.627	0.717
	0.433	0.310	0.427	0.623	0.717
	0.410	0.287	0.440	0.633	0.713
	0.403	0.300	0.440	0.643	0.723
	0.407	0.323	0.440	0.640	0.733
	0.407	0.320	0.440	0.630	0.740
	0.403	0.330	0.427	0.627	0.737
	0.393	0.333	0.413	0.627	0.733
	0.403	0.373	0.420	0.630	0.723
	0.423	0.373	0.430	0.633	0.707
225	0.497	0.630	0.577	0.453	0.800
	0.500	0.623	0.567	0.473	0.800
	0.463	0.603	0.560	0.487	0.803
	0.440	0.587	0.547	0.460	0.803
	0.430	0.583	0.523	0.457	0.790
	0.440	0.603	0.493	0.453	0.793
	0.433	0.613	0.480	0.447	0.780
	0.443	0.607	0.490	0.437	0.787
	0.443	0.603	0.500	0.417	0.787
	0.457	0.603	0.507	0.433	0.793
	0.467	0.610	0.510	0.440	0.797
	0.467	0.593	0.523	0.443	0.793
	0.463	0.587	0.533	0.453	0.790
	0.457	0.593	0.537	0.457	0.793
	0.467	0.607	0.540	0.463	0.793
	0.467	0.617	0.537	0.450	0.807
	0.453	0.620	0.543	0.457	0.803
	0.440	0.623	0.547	0.457	0.793
	0.433	0.613	0.550	0.470	0.793
	0.433	0.610	0.557	0.473	0.797

Table A2.9. Greenhouse green NDVI as affected by corn growth stage and N rate at 75 cm row spacing.

	Corn Growth Stage				
	V8	V9	V10	V11	V12
N Rate (kg ha^{-1})	------------------	------------------	Green NDVI	------------------	------------------
0	0.437	0.200	0.280	0.290	0.373
	0.447	0.190	0.283	0.293	0.390
	0.460	0.223	0.267	0.297	0.397
	0.437	0.217	0.250	0.300	0.390
	0.430	0.197	0.250	0.307	0.387
	0.410	0.190	0.243	0.307	0.363
	0.370	0.217	0.253	0.267	0.370
	0.387	0.203	0.260	0.270	0.353
	0.390	0.197	0.277	0.253	0.410
	0.420	0.180	0.280	0.277	0.407
	0.443	0.200	0.273	0.263	0.413
	0.453	0.213	0.273	0.283	0.390
	0.467	0.260	0.280	0.280	0.400
	0.440	0.247	0.287	0.263	0.420
	0.437	0.240	0.277	0.240	0.390
	0.443	0.203	0.270	0.233	0.370
	0.467	0.250	0.260	0.247	0.363
	0.470	0.223	0.243	0.237	0.383
	0.487	0.223	0.233	0.237	0.387
	0.467	0.200	0.227	0.247	0.380
75	0.347	0.267	0.340	0.560	0.730
	0.327	0.280	0.313	0.560	0.730
	0.337	0.297	0.310	0.553	0.730
	0.323	0.313	0.267	0.540	0.727
	0.347	0.303	0.280	0.520	0.727
	0.357	0.297	0.300	0.503	0.733
	0.377	0.280	0.323	0.507	0.730
	0.373	0.257	0.333	0.500	0.733
	0.380	0.263	0.350	0.490	0.730
	0.373	0.230	0.333	0.483	0.733
	0.387	0.257	0.323	0.497	0.733
	0.373	0.273	0.277	0.523	0.737
	0.370	0.297	0.287	0.550	0.737
	0.350	0.280	0.250	0.567	0.730
	0.347	0.257	0.253	0.577	0.730
	0.343	0.233	0.267	0.577	0.730
	0.353	0.213	0.297	0.583	0.733
	0.370	0.180	0.303	0.583	0.727
	0.360	0.173	0.257	0.580	0.727
	0.367	0.193	0.243	0.577	0.723

	Corn Growth Stage				
	V8	V9	V10	V11	V12
N Rate (kg ha^{-1})	-----------	-----------	Amber NDVI	-----------	-----------
150	0.333	0.217	0.473	0.633	0.793
	0.333	0.213	0.470	0.633	0.770
	0.337	0.227	0.480	0.627	0.753
	0.327	0.223	0.460	0.623	0.757
	0.333	0.297	0.463	0.623	0.760
	0.350	0.233	0.460	0.623	0.773
	0.367	0.237	0.490	0.623	0.787
	0.370	0.190	0.483	0.630	0.790
	0.357	0.217	0.490	0.630	0.793
	0.343	0.237	0.483	0.623	0.780
	0.343	0.227	0.483	0.613	0.777
	0.340	0.210	0.477	0.603	0.780
	0.347	0.200	0.467	0.607	0.783
	0.353	0.207	0.470	0.603	0.793
	0.370	0.243	0.480	0.620	0.777
	0.373	0.230	0.477	0.620	0.773
	0.380	0.250	0.490	0.627	0.767
	0.363	0.213	0.477	0.620	0.790
	0.370	0.260	0.477	0.773	0.793
	0.337	0.253	0.633	0.793	0.780
225	0.397	0.527	0.620	0.357	0.687
	0.410	0.517	0.613	0.363	0.713
	0.387	0.503	0.593	0.350	0.720
	0.407	0.500	0.597	0.343	0.727
	0.407	0.510	0.613	0.347	0.717
	0.430	0.530	0.630	0.350	0.700
	0.417	0.543	0.637	0.323	0.710
	0.403	0.543	0.627	0.280	0.700
	0.387	0.540	0.623	0.280	0.727
	0.373	0.523	0.613	0.303	0.707
	0.367	0.523	0.603	0.343	0.697
	0.380	0.503	0.590	0.350	0.687
	0.393	0.500	0.593	0.353	0.697
	0.407	0.497	0.603	0.323	0.713
	0.407	0.493	0.617	0.323	0.713
	0.400	0.510	0.620	0.317	0.717
	0.390	0.497	0.623	0.333	0.703
	0.380	0.513	0.620	0.333	0.693
	0.397	0.507	0.623	0.353	0.687
	0.413	0.533	0.613	0.343	0.707

Table A2.10. Greenhouse Amber, Red and Green NDVI as affected by sensor movement speed over the maize canopy and N Rate.

Amber NDVI

	Nitrogen Rate (kg ha^{-1})				
	0	75	150	225	
	--------NDVI--------				
Sensor Movement					**Average**
Fast	0.379	0.502	0.547	0.593	0.505
Slow	0.367	0.498	0.550	0.597	0.503
Stationary	0.361	0.502	0.556	0.604	0.506

Red NDVI

	Nitrogen Rate (kg ha^{-1})				
	0	75	150	225	
	--------NDVI--------				
Sensor Movement					**Average**
Fast	0.397	0.595	0.664	0.703	0.590
Slow	0.483	0.620	0.706	0.748	0.639
Stationary	0.455	0.612	0.696	0.747	0.627

Green NDVI

	Nitrogen Rate (kg ha^{-1})				
	0	75	150	225	
	--------NDVI--------				
Sensor Movement					**Average**
Fast	0.245	0.413	0.506	0.527	0.423
Slow	0.352	0.464	0.547	0.585	0.487
Stationary	0.339	0.470	0.552	0.590	0.488

Table A2.11. Greenhouse average Green NDVI across maize row spacing, maize growth stage and N rate.

	Nitrogen Rate (kg ha^{-1})			
	0	75	150	225
	NDVI			
Nitrogen Rate Average	0.312	0.449	0.535	0.564
Row Spacing		**V8**		
25 cm	0.516	0.508	0.540	0.523
50 cm	0.379	0.368	0.380	0.474
75 cm	0.373	0.375	0.381	0.403
		V9		
25 cm	0.340	0.347	0.539	0.563
50 cm	0.244	0.289	0.335	0.519
75 cm	0.233	0.222	0.310	0.483
		V10		
25 cm	0.296	0.397	0.573	0.470
50 cm	0.175	0.326	0.440	0.454
75 cm	0.210	0.317	0.445	0.511
		V11		
25 cm	0.303	0.576	0.629	0.632
50 cm	0.236	0.465	0.589	0.556
75 cm	0.251	0.450	0.537	0.539
		V12		
25 cm	0.457	0.720	0.813	0.796
50 cm	0.325	0.688	0.758	0.794
75 cm	0.341	0.686	0.759	0.749

APPENDIX C

Table A3.1. Amber NDVI for site year 1 and 2 by treatment replication as affected by maize growth stage and applied N rate.

Site Year	Rate	Rep	------------------------Amber NDVI------------------------				
	(kg ha^{-1})		V8	V10	V12	V14	V16
1	0	1	0.259	0.369	0.387	0.561	0.583
1	0	2	0.277	0.392	0.359	0.551	0.558
1	0	3	0.253	0.354	0.365	0.527	0.602
1	0	4	0.292	0.420	0.383	0.563	0.633
1	50	1	0.460	0.508	0.536	0.661	0.661
1	50	2	0.420	0.514	0.543	0.656	0.665
1	50	3	0.401	0.625	0.584	0.660	0.674
1	50	4	0.378	0.534	0.543	0.634	0.667
1	100	1	0.451	0.571	0.640	0.709	0.700
1	100	2	0.412	0.582	0.607	0.670	0.704
1	100	3	0.447	0.569	0.627	0.699	0.696
1	100	4	0.405	0.601	0.555	0.688	0.697
1	175	1	0.431	0.609	0.670	0.698	0.707
1	175	2	0.412	0.623	0.646	0.715	0.724
1	175	3	0.435	0.582	0.624	0.706	0.719
1	175	4	0.380	0.562	0.627	0.700	0.719
2	0	1	0.305	0.416	0.403	0.556	0.621
2	0	2	0.342	0.423	0.368	0.557	0.579
2	0	3	0.341	0.462	0.361	0.542	0.571
2	0	4	0.376	0.419	0.396	0.475	0.549
2	50	1	0.393	0.524	0.533	0.631	0.661
2	50	2	0.437	0.530	0.517	0.653	0.658
2	50	3	0.419	0.567	0.554	0.608	0.634
2	50	4	0.487	0.616	0.583	0.613	0.591
2	100	1	0.395	0.585	0.635	0.705	0.677
2	100	2	0.410	0.582	0.630	0.681	0.702
2	100	3	0.499	0.607	0.615	0.636	0.671
2	100	4	0.486	0.571	0.618	0.683	0.690
2	175	1	0.435	0.609	0.638	0.684	0.722
2	175	2	0.464	0.603	0.647	0.677	0.695
2	175	3	0.450	0.600	0.656	0.696	0.708
2	175	4	0.403	0.630	0.631	0.692	0.692

Table A3.2. Red NDVI for site year 1 and 2 by treatment replication as affected by maize growth stage and applied N rate.

Site Year	Rate	Rep	Red NDVI			
	(kg ha^{-1})		V8	V10	V12	V14
1	0	1	0.228	0.404	0.464	0.713
1	0	2	0.234	0.397	0.473	0.719
1	0	3	0.249	0.400	0.469	0.639
1	0	4	0.265	0.448	0.505	0.714
1	50	1	0.341	0.641	0.641	0.815
1	50	2	0.352	0.613	0.705	0.794
1	50	3	0.372	0.580	0.690	0.819
1	50	4	0.329	0.623	0.711	0.784
1	100	1	0.335	0.643	0.763	0.861
1	100	2	0.372	0.654	0.711	0.860
1	100	3	0.339	0.649	0.732	0.850
1	100	4	0.354	0.584	0.717	0.841
1	175	1	0.376	0.669	0.791	0.845
1	175	2	0.401	0.637	0.770	0.857
1	175	3	0.383	0.653	0.738	0.870
1	175	4	0.302	0.630	0.739	0.866
2	0	1	0.273	0.465	0.542	0.708
2	0	2	0.319	0.455	0.484	0.693
2	0	3	0.365	0.521	0.450	0.642
2	0	4	0.356	0.482	0.489	0.708
2	50	1	0.389	0.568	0.661	0.818
2	50	2	0.402	0.644	0.642	0.814
2	50	3	0.382	0.637	0.696	0.788
2	50	4	0.513	0.699	0.746	0.807
2	100	1	0.377	0.648	0.738	0.848
2	100	2	0.381	0.635	0.764	0.836
2	100	3	0.504	0.696	0.769	0.836
2	100	4	0.500	0.647	0.742	0.810
2	175	1	0.389	0.660	0.749	0.861
2	175	2	0.447	0.698	0.777	0.848
2	175	3	0.465	0.717	0.792	0.805
2	175	4	0.434	0.680	0.721	0.827

Table A3.3. Green NDVI for site year 1 and 2 by treatment replication as affected by maize growth stage and applied N rate.

Site Year	Rate	Rep	------------------Green NDVI----------------------			
	(kg ha^{-1})		V8	V10	V12	V14
1	0	1	0.345	0.417	0.419	0.510
1	0	2	0.351	0.486	0.408	0.513
1	0	3	0.357	0.408	0.418	0.510
1	0	4	0.395	0.513	0.419	0.481
1	50	1	0.429	0.606	0.567	0.493
1	50	2	0.405	0.526	0.586	0.497
1	50	3	0.461	0.593	0.556	0.473
1	50	4	0.408	0.527	0.582	0.491
1	100	1	0.338	0.511	0.645	0.500
1	100	2	0.376	0.565	0.589	0.496
1	100	3	0.439	0.606	0.624	0.517
1	100	4	0.414	0.611	0.595	0.498
1	175	1	0.475	0.642	0.658	0.525
1	175	2	0.473	0.612	0.605	0.473
1	175	3	0.387	0.585	0.608	0.486
1	175	4	0.357	0.574	0.585	0.526
2	0	1	0.401	0.482	0.419	0.484
2	0	2	0.367	0.508	0.378	0.494
2	0	3	0.440	0.469	0.416	0.454
2	0	4	0.386	0.481	0.415	0.454
2	50	1	0.436	0.565	0.558	0.511
2	50	2	0.448	0.579	0.516	0.495
2	50	3	0.394	0.551	0.549	0.483
2	50	4	0.511	0.627	0.587	0.501
2	100	1	0.433	0.590	0.603	0.562
2	100	2	0.444	0.601	0.621	0.532
2	100	3	0.506	0.636	0.607	0.513
2	100	4	0.509	0.618	0.632	0.500
2	175	1	0.376	0.575	0.609	0.503
2	175	2	0.498	0.633	0.642	0.500
2	175	3	0.491	0.645	0.656	0.517
2	175	4	0.460	0.581	0.634	0.532

Table A3.4. SPAD chlorophyll for site year 1 and 2 by treatment replication as affected by maize growth stage and applied N rate.

Site Year	Rate	Rep	-----SPAD Chlorophyll-----				
	(kg ha^{-1})		V8	V10	V12	V14	V16
1	0	1	20.1	37.8	29.7	31.8	32.7
1	0	2	24.4	29.7	32.6	36.6	35.6
1	0	3	27.9	31.7	30.5	33.8	34.9
1	0	4	32.2	33.2	28.3	34.5	28.2
1	50	1	46.0	45.5	38.1	37.4	42.8
1	50	2	44.6	43.6	38.8	37.6	42.8
1	50	3	41.7	47.1	36.6	35.3	36.4
1	50	4	45.3	45.9	39.5	42.7	41.4
1	100	1	47.7	47.3	42.8	45.3	48.3
1	100	2	47.9	47.2	43.4	38.8	45.3
1	100	3	23.6	43.8	42.0	29.1	49.6
1	100	4	46.2	48.9	38.4	46.6	48.3
1	175	1	44.1	51.1	44.9	43.1	48.5
1	175	2	45.7	47.8	50.5	41.6	50.3
1	175	3	40.6	48.0	41.6	42.5	43.4
1	175	4	42.9	46.1	43.2	46.9	50.1
2	0	1	37.0	32.4	32.0	31.7	35.1
2	0	2	23.9	29.9	30.9	34.4	39.7
2	0	3	34.1	30.7	29.9	29.2	35.1
2	0	4	34.8	29.8	25.2	30.4	27.4
2	50	1	46.8	43.3	38.8	34.9	28.5
2	50	2	45.2	40.2	36.5	34.6	44.0
2	50	3	41.5	44.5	35.1	38.6	40.9
2	50	4	40.6	44.7	36.7	27.2	54.4
2	100	1	46.6	45.4	41.9	42.2	45.2
2	100	2	46.1	43.9	44.7	42.8	53.6
2	100	3	43.0	39.2	39.0	39.8	58.5
2	100	4	41.3	44.8	43.5	46.1	49.0
2	175	1	45.0	42.8	42.3	50.9	48.9
2	175	2	44.6	44.8	43.8	43.5	47.6
2	175	3	42.1	48.2	46.9	48.0	42.3
2	175	4	43.7	44.6	40.3	44.3	51.6

Table A3.5. Plant height for site year 1 and 2 by treatment replication as affected by maize growth stage and applied N rate.

Site Year	Rate ($kg\ ha^{-1}$)	Rep	Avg Height (cm) V8	V10	V12	V14	V16
1	0	1	23	32	54	55	90
1	0	2	22	37	51	64	90
1	0	3	24	38	50	54	81
1	0	4	25	42	50	58	94
1	50	1	26	58	76	83	126
1	50	2	29	54	74	96	147
1	50	3	32	58	81	105	156
1	50	4	36	52	78	90	133
1	100	1	32	56	76	112	169
1	100	2	29	58	80	96	153
1	100	3	30	57	74	97	159
1	100	4	31	56	79	92	157
1	175	1	31	60	84	107	156
1	175	2	33	57	89	120	171
1	175	3	33	61	77	102	140
1	175	4	29	53	72	106	159
2	0	1	28	43	53	59	95
2	0	2	23	36	52	63	83
2	0	3	23	38	44	56	81
2	0	4	20	37	47	55	84
2	50	1	27	56	73	93	156
2	50	2	32	53	66	80	117
2	50	3	27	50	65	90	121
2	50	4	35	57	76	95	136
2	100	1	28	56	79	95	171
2	100	2	28	50	73	98	157
2	100	3	33	61	80	113	145
2	100	4	35	53	77	98	150
2	175	1	25	53	75	120	157
2	175	2	36	60	83	98	157
2	175	3	26	58	74	91	138
2	175	4	31	55	76	104	164

Table A3.6. Soil N concentration (0-20 cm depth) for site year 1 and 2 by treatment replication as affected by maize growth stage and applied N rate.

Site Year	Rate ($kg\ ha^{-1}$)	Rep	Soil N ($mg\ kg^{-1}$) V8	V10	V12	V14	V16
1	0	1	17.70	24.58	9.65	12.59	10.69
1	0	2	12.05	10.19	25.72	7.80	16.02
1	0	3	12.67	18.72	11.80	25.80	16.22
1	0	4	6.90	16.84	19.03	29.35	14.13
1	50	1	15.97	26.43	65.97	30.89	6.27
1	50	2	17.89	30.45	16.91	89.43	12.02
1	50	3	22.97	47.69	32.21	89.49	22.87
1	50	4	15.28	15.59	12.65	59.24	14.67
1	100	1	40.03	39.30	27.91	14.83	24.72
1	100	2	16.98	27.59	55.50	32.39	27.64
1	100	3	12.34	14.62	12.97	25.37	12.61
1	100	4	27.94	15.00	20.56	37.42	30.17
1	175	1	13.95	20.22	9.95	14.53	8.99
1	175	2	24.18	44.04	20.68	36.23	27.88
1	175	3	21.94	18.65	37.54	89.27	22.82
1	175	4	32.50	31.06	20.71	79.24	68.97
2	0	1	10.63	19.42	24.24	33.03	7.94
2	0	2	21.02	47.27	4.81	25.94	8.40
2	0	3	18.56	17.10	5.73	16.64	11.82
2	0	4	15.87	9.26	4.75	12.32	10.02
2	50	1	15.56	22.62	30.54	83.37	10.69
2	50	2	13.37	9.04	8.38	7.24	10.78
2	50	3	20.15	29.34	7.22	24.18	14.55
2	50	4	12.82	19.18	9.62	17.02	9.79
2	100	1	15.39	32.44	22.41	36.67	23.74
2	100	2	25.41	10.67	26.58	30.97	23.28
2	100	3	11.80	23.24	15.53	20.84	12.66
2	100	4	19.76	58.24	27.78	25.01	15.98
2	175	1	48.80	50.72	43.72	89.25	14.71
2	175	2	47.68	29.33	11.69	14.81	18.19
2	175	3	28.56	6.53	36.51	14.92	18.49
2	175	4	25.20	39.68	7.57	89.91	13.97

Table A3.7. Maize flag leaf N concentration for site year 1 and 2 by treatment replication as affected by maize growth stage and applied N rate.

Site Year	Rate (kg ha^{-1})	Rep	Flag Leaf N mg g^{-1}) V8	V10	V12	V14	V16
1	0	1	2.925	2.689	2.181	2.248	2.968
1	0	2	3.079	2.771	1.984	1.898	1.979
1	0	3	3.280	2.429	2.296	1.931	1.659
1	0	4	2.810	2.778	2.066	1.859	1.567
1	50	1	4.441	3.526	2.406	2.110	2.155
1	50	2	4.571	3.519	2.523	2.438	2.305
1	50	3	4.215	3.671	2.315	2.012	2.346
1	50	4	4.243	4.653	2.740	2.126	1.988
1	100	1	4.768	4.278	3.196	2.571	2.312
1	100	2	4.812	3.830	2.623	2.286	2.384
1	100	3	4.883	3.581	2.849	2.393	.
1	100	4	4.721	4.090	2.618	2.400	2.431
1	175	1	4.498	4.304	3.039	2.499	2.595
1	175	2	4.921	4.194	3.436	3.188	2.921
1	175	3	4.644	4.536	3.480	2.610	2.763
1	175	4	4.700	4.500	3.383	3.175	3.057
2	0	1	2.636	2.412	2.229	1.934	2.325
2	0	2	2.717	3.101	.	2.054	2.084
2	0	3	2.635	2.385	2.049	2.127	1.915
2	0	4	2.980	2.349	2.091	1.864	1.859
2	50	1	4.336	3.581	1.914	2.133	.
2	50	2	4.000	.	2.142	2.012	2.027
2	50	3	4.427	3.376	2.293	2.054	2.159
2	50	4	4.372	3.075	2.399	1.949	2.073
2	100	1	4.532	4.081	3.420	1.805	2.251
2	100	2	4.773	3.894	2.985	2.693	2.562
2	100	3	.	3.896	2.676	2.272	2.225
2	100	4	4.493	4.228	3.201	3.457	2.712
2	175	1	4.817	3.993	3.009	2.862	2.461
2	175	2	4.590	3.903	2.899	2.598	2.447
2	175	3	4.896	4.410	3.164	2.768	2.584
2	175	4	4.869	4.126	2.988	2.993	2.536

Table A3.8. Maize grain yield for site year 1 and 2 by treatment replication as affected by maize growth stage and applied N rate.

Site Year	Rate (kg ha^{-1})	Rep	Grain Yield (Mg ha^{-1})
1	0	1	3.2
1	0	2	3.8
1	0	3	3.6
1	0	4	4.1
1	50	1	7.0
1	50	2	6.5
1	50	3	6.8
1	50	4	7.3
1	100	1	8.5
1	100	2	9.5
1	100	3	7.6
1	100	4	8.2
1	175	1	8.2
1	175	2	8.3
1	175	3	13.2
1	175	4	12.0
2	0	1	3.8
2	0	2	3.7
2	0	3	3.2
2	0	4	2.7
2	50	1	6.1
2	50	2	6.9
2	50	3	6.4
2	50	4	5.9
2	100	1	7.8
2	100	2	7.2
2	100	3	6.8
2	100	4	6.5
2	175	1	7.7
2	175	2	8.0
2	175	3	6.7
2	175	4	7.0

Table A3.9. Amber and red NDVI correlation with SPAD chlorophyll, soil N concentration, maize flag leaf N concentration, plant height, and statistically significant multiple regression for site year 1.

Site Year 1

	Crop Circle	Corn Growth Stage V8 GreenSeeker (Red)	GreenSeeker (Green)
		R-square	
Correlation to NDVI			
SPAD	0.4982	0.5814	0.1059
Soil N	0.1770	0.1082	0.0392
Leaf N	0.8340	0.7528	0.1755
Plant Height	0.4987	0.6538	0.2364
Multiple Regression	----------	----------	----------

	Crop Circle	Corn Growth Stage V10 GreenSeeker (Red)	GreenSeeker (Green)
		R-square	
Correlation to NDVI			
SPAD	0.8506	0.8385	0.6082
Soil N	0.2081	0.1143	0.0396
Leaf N	0.7141	0.7459	0.4657
Plant Height	0.8690	0.9097	0.7697
Multiple Regression	0.9091 (SPAD + Height)	.9377 (Leaf N + Height)	----------

	Crop Circle	Corn Growth Stage V12 GreenSeeker (Red)	GreenSeeker (Green)
		R-square	
Correlation to NDVI			
SPAD	0.8471	0.8264	0.7768
Soil N	0.0364	0.0172	0.0293
Leaf N	0.6871	0.6525	0.5969
Plant Height	0.8488	0.8745	0.8439
Multiple Regression	0.9261 (Leaf N + Height)	.9304 (Leaf N + Height)	.8854 (Leaf N + Height)

	Crop Circle	Corn Growth Stage V14 GreenSeeker (Red)	GreenSeeker (Green)
		R-square	
Correlation to NDVI			
SPAD	0.3246	0.3183	0.0002
Soil N	0.1146	0.1073	0.1288
Leaf N	0.5370	0.4701	0.0116
Plant Height	0.8948	0.8343	0.0269
Multiple Regression	----------	----------	----------

	Crop Circle	Corn Growth Stage V16 GreenSeeker (Red)	GreenSeeker (Green)
		R-square	
Correlation to NDVI			
SPAD	0.5300	----------	----------
Soil N	0.1961	----------	----------
Leaf N	0.2494	----------	----------
Plant Height	0.8228	----------	----------
Multiple Regression	----------	----------	----------

Table A3.10. Amber and red NDVI correlation with SPAD chlorophyll, soil N concentration, maize flag leaf N concentration, plant height, and statistically significant multiple regression for site year 1.

Site Year 2

	Corn Growth Stage V8		
	Crop Circle	GreenSeeker (Red)	GreenSeeker (Green)
	R-square		
Correlation to NDVI			
SPAD	0.2814	0.1822	0.1807
Soil N	0.0510	0.0111	0.0017
Leaf N	0.5961	0.4654	0.2424
Plant Height	0.4931	0.4794	0.6268
Multiple Regression	----------	----------	----------

	Corn Growth Stage V10		
	Crop Circle	GreenSeeker (Red)	GreenSeeker (Green)
	R-square		
Correlation to NDVI			
SPAD	0.8043	0.7785	0.7330
Soil N	0.0327	0.0015	0.0063
Leaf N	0.6742	0.6316	0.7104
Plant Height	0.7820	0.8183	0.8304
Multiple Regression	----------	----------	----------

	Corn Growth Stage V12		
	Crop Circle	GreenSeeker (Red)	GreenSeeker (Green)
	R-square		
Correlation to NDVI			
SPAD	0.8421	0.8159	0.8501
Soil N	0.2454	0.2404	0.2353
Leaf N	0.6448	0.5227	0.6033
Plant Height	0.9044	0.9146	0.8835
Multiple Regression	.9478 (Leaf N + Height)	----------	.9428 (SPAD + Height)

	Corn Growth Stage V14		
	Crop Circle	GreenSeeker (Red)	GreenSeeker (Green)
	R-square		
Correlation to NDVI			
SPAD	0.6376	0.4598	0.3217
Soil N	0.1088	0.1213	0.1370
Leaf N	0.3610	0.1746	0.0644
Plant Height	0.6797	0.8419	0.4351
Multiple Regression	.7660 (SPAD + Height)	----------	----------

	Corn Growth Stage V16		
	Crop Circle	GreenSeeker (Red)	GreenSeeker (Green)
	R-square		
Correlation to NDVI			
SPAD	0.5740	----------	----------
Soil N	0.4415	----------	----------
Leaf N	0.7256	----------	----------
Plant Height	0.7194	----------	----------
Multiple Regression	.8519 (Leaf N + Height)	----------	----------

Table A3.11. Green NDVI correlation with grain yield for site year 1 and 2.

Site Year 1

	Green NDVI
Corn Growth Stage	R^2
V8	0.0229
V10	0.4272
V12	0.5995
V14	0.0006
V16	----------

Site Year 2

	Green NDVI
Corn Growth Stage	R^2
V8	0.1912
V10	0.7015
V12	0.8137
V14	0.5674
V16	----------

Table A3.12. SPAD chlorophyll content, plant height, soil N concentration and maize flag leaf N concentration regression correlation with Amber and red NDVI for site year 1.

	Corn Growth Stage V8	
	Amber NDVI	**Red NDVI**
	---R-square---	
Correlation to NDVI		
SPAD	0.4982	0.5814
Soil N	0.1770	0.1082
Leaf N	0.8340	0.7528
Plant Height	0.4987	0.6538

	Corn Growth Stage V10	
	Amber NDVI	**Red NDVI**
	---R-square---	
Correlation to NDVI		
SPAD	0.8506	0.8385
Soil N	0.2081	0.1143
Leaf N	0.7141	0.7459
Plant Height	0.8690	0.9097

	Corn Growth Stage V12	
	Amber NDVI	**Red NDVI**
	---R-square---	
Correlation to NDVI		
SPAD	0.8471	0.8264
Soil N	0.0364	0.0172
Leaf N	0.6871	0.6525
Plant Height	0.8488	0.8745

	Corn Growth Stage V14	
	Amber NDVI	**Red NDVI**
	---R-square---	
Correlation to NDVI		
SPAD	0.3246	0.3183
Soil N	0.1146	0.1073
Leaf N	0.5370	0.4701
Plant Height	0.8948	0.8343

Table A3.13. SPAD chlorophyll content, plant height, soil N concentration and maize flag leaf N concentration regression correlation with Amber and red NDVI for site year 2.

	Corn Growth Stage V8	
	Amber NDVI	**Red NDVI**
Correlation to NDVI		
SPAD	0.1822	0.1807
Soil N	0.0111	0.0017
Leaf N	0.4654	0.2424
Plant Height	0.4794	0.6268

	Corn Growth Stage V10	
	Amber NDVI	**Red NDVI**
Correlation to NDVI		
SPAD	0.7785	0.7330
Soil N	0.0015	0.0063
Leaf N	0.6316	0.7104
Plant Height	0.8183	0.8304

	Corn Growth Stage V12	
	Amber NDVI	**Red NDVI**
Correlation to NDVI		
SPAD	0.8159	0.8501
Soil N	0.2404	0.2353
Leaf N	0.5227	0.6033
Plant Height	0.9146	0.8835

	Corn Growth Stage V14	
	Amber NDVI	**Red NDVI**
Correlation to NDVI		
SPAD	0.4598	0.3217
Soil N	0.1213	0.1370
Leaf N	0.1746	0.0644
Plant Height	0.8419	0.4351

Table A3.14. SPAD chlorophyll readings in irrigated maize for site years 1 and 2 across 4 maize growth stages and 4 applied Nitrogen rates.

Site Year 1

	Nitrogen Rate (kg ha^{-1})			
	0	50	100	175
	--------------------------SPAD-------------------------			
Corn Growth Stage				
V8	26.2	44.4	41.4	43.3
V10	33.1	45.5	46.8	48.3
V12	30.3	38.3	41.7	45.1
V14	34.2	38.3	40.0	43.5
Analysis of Variance	**P > F**	**LSD 0.10**		
Rate	<0.0001	2.5		
Growth Stage	0.0009	2.7		
N Rate x Growth Stage	0.0736	-----		

Site Year 2

	Nitrogen Rate (kg ha^{-1})			
	0	50	100	175
	--------------------------SPAD-------------------------			
Corn Growth Stage				
V8	32.5	43.5	44.2	43.9
V10	30.7	43.2	43.3	45.1
V12	29.5	36.8	42.3	43.3
V14	31.4	33.8	42.7	46.7
Analysis of Variance	**P > F**	**LSD 0.10**		
Rate	<0.0001	2.6		
Growth Stage	0.0017	2.9		
N Rate x Growth Stage	0.1698	-----		

Table A3.15. Maize plant height for site years 1 and 2 across 4 maize growth stages and 4 applied Nitrogen rates.

Site Year 1

	Nitrogen Rate (kg ha^{-1})			
	0	50	100	175
	----Plant Ht (cm)----			
Corn Growth Stage				
V8	23.8	30.8	30.6	31.6
V10	37.1	55.6	56.7	57.6
V12	51.4	77.0	77.2	80.6
V14	57.6	93.2	99.1	108.8
Analysis of Variance	**P > F**	**LSD 0.10**		
Rate	<0.0001	4.1		
Growth Stage	<0.0001	4.5		
N Rate x Growth Stage	<0.0001	8.1		

Site Year 2

	Nitrogen Rate (kg ha^{-1})			
	0	50	100	175
	----Plant Ht (cm)----			
Corn Growth Stage				
V8	23.5	30.3	31.0	29.5
V10	38.6	54.1	55.1	56.5
V12	49.2	70.0	77.2	77.0
V14	57.9	89.3	100.8	102.8
Analysis of Variance	**P > F**	**LSD 0.10**		
Rate	<0.0001	4.4		
Growth Stage	<0.0001	4.9		
N Rate x Growth Stage	<0.0001	8.8		

Table A3.16. Soil Nitrate-Nitrogen concentration (0-20 cm depth) in irrigated maize for site years 1 and 2 across 4 maize growth stages and 4 applied Nitrogen rates.

Site Year 1

	Nitrogen Rate (kg ha^{-1})			
	0	50	100	175
	Soil N (mg kg^{-1})			
Corn Growth Stage				
V8	12.3	18.0	24.3	23.1
V10	17.6	30.0	24.1	28.5
V12	16.5	31.9	29.2	22.2
V14	18.9	67.3	27.5	54.8
Analysis of Variance	**P > F**	**LSD 0.10**		
Rate	0.0046	9.9		
Growth Stage	0.0010	11.1		
N Rate x Growth Stage	0.1033	-----		

Site Year 2

	Nitrogen Rate (kg ha^{-1})			
	0	50	100	175
	Soil N (mg kg^{-1})			
Corn Growth Stage				
V8	16.5	15.5	18.1	37.6
V10	23.3	20.0	31.1	31.6
V12	9.9	13.9	23.1	24.9
V14	22.0	33.0	28.4	52.2
Analysis of Variance	**P > F**	**LSD 0.10**		
Rate	0.0065	9.6		
Growth Stage	0.0050	10.7		
N Rate x Growth Stage	0.8727	-----		

Table A3.17. Irrigated maize flag leaf total Nitrogen concentration for site years 1 and 2 across 4 maize growth stages and 4 applied Nitrogen rates.

Site Year 1

	Nitrogen Rate (kg ha^{-1})			
	0	50	100	175
	------------------Plant N (mg kg^{-1})------------------			
Corn Growth Stage				
V8	3.0	4.4	4.8	4.7
V10	2.7	3.8	3.9	4.4
V12	2.1	2.5	2.8	3.3
V14	2.0	2.2	2.4	2.9
Analysis of Variance	**P > F**	**LSD $_{0.10}$**		
Rate	<0.0001	0.2		
Growth Stage	<0.0001	0.2		
N Rate x Growth Stage	0.0002	0.3		

Site Year 2

	Nitrogen Rate (kg ha^{-1})			
	0	50	100	175
	------------------Plant N (mg kg^{-1})------------------			
Corn Growth Stage				
V8	2.7	4.3	4.6	4.8
V10	2.6	3.3	4.0	4.1
V12	2.1	2.2	3.1	3.0
V14	2.0	2.0	2.6	2.8
Analysis of Variance	**P > F**	**LSD $_{0.10}$**		
Rate	<0.0001	0.2		
Growth Stage	<0.0001	0.2		
N Rate x Growth Stage	<0.0001	0.3		

Table A3.18. Amber and Red NDVI algorithm index ($NDVI_{N\ Applied\ Plot}$ / $NDVI_{0\ N\ Applied\ Plot}$) at site year 1 based on V12 maize growth N response to N application rates of 175, 100, 50 and 0 kg ha^{-1}.

Amber NDVI†	Red NDVI†	N Rate (kg ha^{-1})	Site Year	Amber NDVI†	Red NDVI†	N Rate (kg ha^{-1})	Site Year
1.898	1.706	175	1	1.666	1.382	50	1
1.879	1.661	175	1	1.650	1.520	50	1
1.810	1.591	175	1	1.589	1.487	50	1
1.801	1.593	175	1	1.579	1.534	50	1
1.798	1.672	175	1	1.560	1.354	50	1
1.783	1.628	175	1	1.544	1.489	50	1
1.746	1.559	175	1	1.526	1.457	50	1
1.729	1.561	175	1	1.511	1.503	50	1
1.717	1.688	175	1	1.487	1.368	50	1
1.716	1.644	175	1	1.480	1.504	50	1
1.707	1.575	175	1	1.478	1.472	50	1
1.699	1.577	175	1	1.466	1.518	50	1
1.665	1.568	175	1	1.455	1.270	50	1
1.655	1.527	175	1	1.446	1.397	50	1
1.636	1.462	175	1	1.411	1.367	50	1
1.626	1.464	175	1	1.403	1.410	50	1
1.792	1.644	100	1	1.000	1.000	0	1
1.784	1.534	100	1	1.000	1.000	0	1
1.774	1.579	100	1	1.000	1.000	0	1
1.766	1.546	100	1	1.000	1.000	0	1
1.717	1.611	100	1	1.000	1.000	0	1
1.709	1.503	100	1	1.000	1.000	0	1
1.701	1.547	100	1	1.000	1.000	0	1
1.700	1.515	100	1	1.000	1.000	0	1
1.698	1.627	100	1	1.000	1.000	0	1
1.691	1.518	100	1	1.000	1.000	0	1
1.638	1.562	100	1	1.000	1.000	0	1
1.628	1.530	100	1	1.000	1.000	0	1
1.586	1.511	100	1	1.000	1.000	0	1
1.570	1.409	100	1	1.000	1.000	0	1
1.512	1.451	100	1	1.000	1.000	0	1
1.503	1.421	100	1	1.000	1.000	0	1

†NDVI = $NDVI_{N\ Applied\ Plot}$ / $NDVI_{0\ N\ Applied\ Plot}$ (Plot Rep Averages (All possible combinations))

Table A3.19. Amber and Red NDVI algorithm index ($NDVI_{N\ Applied\ Plot}$ / $NDVI_{0\ N\ Applied\ Plot}$) at site year 2 based on V12 maize growth N response to N application rates of 175, 100, 50 and 0 kg ha^{-1}.

Amber NDVI†	Red NDVI†	N Rate (kg ha^{-1})	Site Year	Amber NDVI†	Red NDVI†	N Rate (kg ha^{-1})	Site Year
1.807	1.483	175	2	1.597	1.219	50	2
1.791	1.434	175	2	1.570	1.185	50	2
1.777	1.461	175	2	1.524	1.283	50	2
1.761	1.430	175	2	1.498	1.376	50	2
1.746	1.549	175	2	1.479	1.366	50	2
1.724	1.607	175	2	1.475	1.327	50	2
1.716	1.637	175	2	1.454	1.438	50	2
1.694	1.489	175	2	1.452	1.542	50	2
1.669	1.664	175	2	1.408	1.468	50	2
1.654	1.726	175	2	1.385	1.426	50	2
1.642	1.759	175	2	1.384	1.544	50	2
1.628	1.600	175	2	1.366	1.557	50	2
1.612	1.533	175	2	1.360	1.352	50	2
1.592	1.590	175	2	1.344	1.313	50	2
1.586	1.620	175	2	1.278	1.422	50	2
1.566	1.474	175	2	1.257	1.526	50	2
1.768	1.361	100	2	1.000	1.000	0	2
1.738	1.409	100	2	1.000	1.000	0	2
1.713	1.418	100	2	1.000	1.000	0	2
1.695	1.368	100	2	1.000	1.000	0	2
1.684	1.525	100	2	1.000	1.000	0	2
1.666	1.579	100	2	1.000	1.000	0	2
1.661	1.589	100	2	1.000	1.000	0	2
1.633	1.533	100	2	1.000	1.000	0	2
1.633	1.639	100	2	1.000	1.000	0	2
1.607	1.696	100	2	1.000	1.000	0	2
1.582	1.707	100	2	1.000	1.000	0	2
1.565	1.647	100	2	1.000	1.000	0	2
1.557	1.509	100	2	1.000	1.000	0	2
1.540	1.562	100	2	1.000	1.000	0	2
1.534	1.572	100	2	1.000	1.000	0	2
1.509	1.517	100	2	1.000	1.000	0	2

†NDVI = $NDVI_{N\ Applied\ Plot}$ / $NDVI_{0\ N\ Applied\ Plot}$ (Plot Rep Averages (All possible combinations))

Table A3.20. Colorado State University, USDA Missouri and USDA Nebraska Amber NDVI algorithm N requirement estimations based on NDVI readings collected at site year 1 and site year 2.

Site Year 1	Applied Nitrogen Rate (kg ha^{-1})†			
	0	50	100	175
	----------N Requirement Estimation (kg ha^{-1})---------			
Colorado State‡	130a	28a	13a	6a
USDA Missouri	166b	84b	60b	51b
USDA Nebraska	173b	54c	29c	9a
Analysis of Variance	**P > F**	**$LSD_{0.10}$**		
Algorithm x Rate	<0.0001	9		

Site Year 2	Applied Nitrogen Rate (kg ha^{-1})†			
	0	50	100	175
	----------N Requirement Estimation (kg ha^{-1})---------			
Colorado State‡	122a	29a	8a	5a
USDA Missouri	163b	87b	69b	50b
USDA Nebraska	173c	55c	16c	7a
Analysis of Variance	**P > F**	**$LSD_{0.10}$**		
Algorithm x Rate	<0.0001	9		

†Nitrogen applied at corn emergence

‡Colorado State and USDA Nebraska Algorithms were used at the V12 corn growth stage, USDA Missouri was used at the V10 corn growth stage.

Table A3.21. Colorado State University, USDA Missouri and Oklahoma State University Red NDVI N algorithm N requirement estimations based on NDVI readings collected at site year 1 and site year 2.

Site Year 1	**Applied Nitrogen Rate (kg ha^{-1})†**			
	0	50	100	175
	----------N Requirement Estimation (kg ha^{-1})---------			
Colorado State‡	124a	28a	14a	8a
USDA Missouri	156b	68b	59b	52b
Oklahoma State	150b	66b	56b	62c
Analysis of Variance	**P > F**	**$LSD_{0.10}$**		
Algorithm x Rate	<0.0001	9		

Site Year 2	**Applied Nitrogen Rate (kg ha^{-1})†**			
	0	50	100	175
	----------N Requirement Estimation (kg ha^{-1})---------			
Colorado State‡	116a	26a	7a	7a
USDA Missouri	154b	80b	69b	49b
Oklahoma State	69c	70c	59c	45b
Analysis of Variance	**P > F**	**$LSD_{0.10}$**		
Algorithm x Rate	<0.0001	9		

†Nitrogen applied at corn emergence

‡Colorado State Algorithm was used at the V12 corn growth stage, USDA Missouri and Oklahoma State algorithm was used at the V10 corn growth stage.

Table A3.22. USDA Missouri and USDA Nebraska Amber NDVI RI based active sensor N recommendation algorithms.

USDA Missouri†:

N Rate ($kg\ ha^{-1}$) = 250 x $ratio_{target}$ / $ratio_{reference}$) - 200

Where:

ratio = visible/near infrared

USDA Nebraska:

$NAPP_{NDVI}$ – 179 $kg\ N\ ha^{-1}$ - CNS_{NDVI}

Where:

NAPP = Nitrogen Application Rate

$CNS_{NDVI} = \{-0.002 - [0.000004 + 0.0000224 \times (0.8073 - (0.4882SI_{NDVI} + 0.5002))]^{1/2}\} / (-0.0000112)$

$SI_{NDVI} = (NDVI - 0.5002) / 0.4882$

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†USDA Missouri has developed algorithms for both the amber and red NDVI sensors.

Table A3.23. USDA Missouri and Oklahoma State University red NDVI RI based active sensor N recommendation algorithms.

USDA Missouri[†]**:**

N Rate (kg ha^{-1}) = 170 x $ratio_{target}$ / $ratio_{reference}$) - 120

Where:

ratio = visible/near infrared

Oklahoma State University:

$R_n = (((YPoN_g) / \varepsilon_n) \times (RI - 1)) \times ((CV_{Cap} - CV_{Plot}) / (CV_{Cap} - CV_{Critical}))$

Where:

R_n = N application rate (kg ha^{-1})

N_g = N content in grain (0.0125 kg ha^{-1})

E_n = Expected NUE

RI = Adjusted RI = (($NDVI_{N\ Rich}$ / $NDVI_{Farmer}$) x 1.64) – 0.528

CV_{Cap} = Maximum coefficient of variation

$CV_{Critical}$ = (-0.0003 x plant population) + 36.315

CV_{Plot} = Coefficient of variation from the plot's NDVI readings

YPo = Yield Potential

[†]USDA Missouri has developed algorithms for both the amber and red NDVI sensors.

Figure A3.1. First derivative of corn grain yield as affected by applied N rate at site years 1 and 2.