EVALUATION OF ACTIVE OPTICAL GROUND-BASED SENSORS TO DETECT EARLY NITROGEN DEFICIENCIES IN CORN

A Dissertation
Submitted to the Graduate Faculty
of the
North Dakota State University
of Agriculture and Applied Sciences

By
Lakesh Kumar Sharma

In Partial Fulfillment of the Requirements
for the Degree of
DOCTOR OF PHILOSOPHY

Major Department:
Soil Sciences

April 2014

Fargo, North Dakota

North Dakota State University
Graduate School

Title

EVALUATION OF ACTIVE OPTICAL GROUND-BASED SENSORS TO DETECT EARLY NITROGEN DEFICIENCIES IN CORN

By
Lakesh Kumar Sharma

The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

DOCTOR OF PHILOSOPHY

SUPERVISORY COMMITTEE:

Dave Franzen, Ph.D.
Chair

Thomas DeSutter, Ph.D.

R. J. Goos, Ph.D.

Joel Ransom, Ph.D.

Approved:

04/09/2014
Date

Francis Casey
Department Chair

ABSTRACT

Corn (*Zea mays*, L) is an important world crop used as livestock feed, human consumption and ethanol production. Early in-season loss of nitrogen (N) continues to be a problem in corn. Ground-based active optical sensors (GBAO) have shown very promising results in predicting crop yield. In these experiments, two GBAO sensors GS and CC were used within forty-six established corn N-rate trials in North Dakota at the six (V6) and twelve (V12) leaf growth stages in 2011, 2012, and 2013. Corn height at V6 and V12 was recorded manually at each site in all three years. At V6, the GS relationship to yield and the INSEY (INSEY = in-season estimate of yield = sensor NDVI / growing degree days from planting date) value was often improved when the sensor NDVI was multiplied times corn height. Segregating the data sets into sites with eastern high clay conventional-till sites surface soil textures (clay more than 30%) and sites with more medium textures improved all INSEY relationships compared to pooling all sites. Eastern high clay conventional-till sites and eatstern medium textured converntional-till sites were further divided into those higher in productivity (yields greater than 10 Mg ha^{-1}) and those lower in productivity (yields less than 10 Mg ha^{-1}). The data categories differed in their sensor relationships to yield. Within all categories, the sensor relationships at V6 were weaker than those at V12. In the lower yielding eastern high clay conventional-till sites, lower yielding eastern medium-textured conventional-till sites, and the eastern no-till sites, no significant relationship was found at V6. At V12, a relatively weak relationship was only found in the low yielding eastern medium-textured coventional-till sites. The GS and CC were found to identify S deficiency at two sites in 2013. Both sensors detected that as N rate increased, the sensor readings generally decreased. This concept could be used by practitioners to screen sites with early season S deficiency, using an N rich strip in the field.

ACKNOWLEDGEMENTS

I would like to express my deep gratitude to Dr. Dave Franzen, my research supervisors, for their guidance, enthusiastic encouragement, and useful critiques of this research work. I would also like to thank Dr. Tom DeSutter, Dr. R.J. Goos, and Dr. Joel Ransom, for their advice and assistance in keeping my progress on schedule.

I am grateful to my collegue, Honggang Bu and student helper, Brad Schmidt, and Eric Schultz for their help in completing this project.

I would also like to extend my thanks to Joel Bell and Norm Cattanach, Rseearch Specialists, Department of Soil for their help in planting and harvesting of my corn.

Finally, I wish to thank North Dakota Corn Council, IPNI and Pioneer Hi-Bred International for their support of this project.

DEDICATION

This dissertation is dedicated to my advisor Dr. Dave Franzen who has been my guide, philosopher, and friend and my wife Sukhwinder Bali who has always stood by me and believed that I could do it.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

LIST OF ABBREVIATIONS

BW .... Band width

CC .... Crop Circle

CI .... Chlorophyll index

CV .... Coefficient of variation

DTPA .... Diethylene triamine pentaacetic acid

EC .... Electrical conductivity

EONR .... Economic optimum nitrogen rate

GBAO .... Ground based active optical

GNDVI .... Green normalized difference vegetative index

GS .... GreenSeeker

INSEY .... Inseason estimation of yield

K .... Potassium

LAI .... Leaf area index

MZ .... Management zone

N .... Nitrogen

NDSU .... North Dakota State University

NDVI .... Normalized difference vegetative index

NDVIH .... Normalized difference vegetative index multiplied times height

NIR .... Near infrared

NNI ....Nitrogen nutrition index

NUE ....Nitrogen use efficiency

P ....Phosphorous

PSNT.. Pre-sidedress nitrate test

S ....Sulfur

SI... Sufficiency index

TSAVI .... Transformed soil adjusted vegetative index

UAN.. urea-ammonium nitrate

USDA.. United States Department of Agriculture

Zn .... Zinc

CHAPTER I. INTRODUCTION

Corn (*Zea mays*, L.) is an important crop in North Dakota used primarily as livestock feed and for ethanol production. Approximately 1.008 million ha of average corn has been planted in North Dakota, with the average yield ranging from 5044-10641 kg ha^{-1} within the last five years, 2008-2012, (USDA-NASS, 2012).

Nitrogen (N) is the most important nutrient for crop production and it is applied by growers in large amounts. Nitrogen is a component of structural, genetic, and metabolic compounds in plant cells. It is a major component of chlorophyll, the compound in plants responsible for photosynthesis. Nitrogen is made available in soil from organic matter mineralization, N- fixing bacteria, blue-green algae and N released through plant residue decay. Most mineral soils do not release sufficient N to support the high yields expected by growers, therefore, supplemental N must be applied.

The recommended N rate for corn in North Dakota is currently determined by a formula that includes yield expectations, soil test nitrate analysis before planting to 60-cm in depth, and any N credits from previous crops. The efficient use of N for corn production is important to maximize economic return and minimize N losses to the environment. Nitrogen use efficiency (NUE) has been widely used as a metric to relate N uptake with the quantity of N applied. One way to explain NUE is in terms of the mass of grain harvested compared to the mass of N applied. Because there is considerable yield variability and N loss potential variability within fields, and volatility in N fertilizer prices and corn prices over time, developing fertilization practices that can optimize the N fertilizer rates in-season could enhance grower profitability and NUE.

Nitrogen is a difficult nutrient to manage in crop production because it can volatilize directly into the atmosphere, or it can be leached, immobilized, fixed, or transformed to nitrous oxides or nitrogen gas and made unavailable for plant uptake (Cassman et al., 2002). Nitrogen is present in several forms in soil. Fertilizer, both organic and inorganic, may contain ammonia or ammonium and nitrate. Nitrate is a plant-available form of N. Due to its negative charge, it cannot be held by the negatively charged soil particles. Nitrate is therefore susceptible to leaching through the soil deep enough that plant roots are unable to capture it. Leached nitrate can seep into groundwater supplies that are tapped by private and municipal water supplies, or it can move laterally to surface water in ponds, lakes, streams and rivers, contributing to eutrophication in continental environments, and even in ocean environments such as the Gulf of Mexico (Schilling, 2002). Present N management has raised serious concerns over the pollution of natural water reservoirs and ground water by nitrate contamination from the Corn Belt of the USA (Schilling, 2002; CAST, 1999; Steinheimer et al., 1998). The amount N has greatly increased in the Gulf of Mexico through the Mississippi river (Turner and Rabalais, 1991), which has caused serious hypoxia in the coastal water (Rabalais et al., 1991).

Typically, farmers apply N before planting (Cassman et al., 2002). Scharf et al., (2002) in Missouri reported that N application in the fall is at a major risk for spring N loss, which results in corn yield loss. The time between N application and its active absorption by the crop provides numerous opportunities for N loss from leaching, clay fixation, immobilization, denitrification, and volatilization (Scharf et al., 2002).

Initial soil N varies across a field, as does the N mineralization and potential losses. If a uniform N rate is applied to a field, it may result in over-fertilized and under-fertilized areas, which lowers the yield potential of the entire field. Fertilizer N applied at the EONR (economical optimal N rate) would tend to minimize N loss and its associated environmental problems, where rate is the only factor contributing to NUE. The ideal N application for any single location within a field is the amount of N needed to optimize profitability for the farmer. However, even if the EONR is applied within the field, high rainfall early in the growing season can produce high N loss through leaching or denitrification, changing the available N supply within a matter of days from optimal to deficient. Therefore, there is need to develop management practices that improve NUE through both rate and timing in order to maintain a high yields and reduce unfavorable environmental influences.

The first step to optimizing N use is to determine the variability of N in a field. Various techniques are currently used to determine this variability, including zone soil nitrate testing (Franzen et al., 2002). Zone soil nitrate testing is useful in determining residual nitrate left after the previous crop harvest, however, it cannot predict gains or losses of soil N the following spring to early summer of the next growing season. A strategy that for implementing in-season N application is based on the use of ground-based active-optical (GBAO) sensors such as the GS and CC. Ground-based active-optical crop sensors can be used at any pre-flowering growth stage of crop without consideration of clouds and ambient light. The GBAO sensors were developed using certain light-spectrum wavelengths related to crop biomass or leaf chlorophyll. The basic theory of the sensors is that healthy plants will absorb more light in red region, which corresponds to greater chlorophyll content. The red/near-infrared ratio can be used to estimate leaf area index (LAI), green biomass, crop yield potential, and crop photosynthetic capacity (Araus, 1996). The LAI is a ratio of surface area of vegetation divided by the area of land on which it is grown. The GBAO sensors emit a coded light of specific wavelengths onto crop foliage. This light reflected back and measured by the device. Estimates of yield deficiency are made using algorithm that are constructed using empirical data from each crop.

The thesis is organized into eight different chapter including introduction as first chapter. The literature review discussed the different approached sued to predict the yield, nutrient variations, nutrient deficiencies, different approached used to calculate the required N in deifferent crops. Although the type of method used to analyse specific nutrient ha been methined in every results chapter (IV to VII) but they are elaborated in chapter III with chemical value at the end of thesis as appendix. Chapter IV dicussed the sensors ability to predict the corn yiled and use of corn height to improve the relationsahip between the sensor reading and corn yield. Comparison between the two sensors for predicting yield early in the season has been discussed in chapter V whereas, algorithms using different sensor wavelength were buit and decisibed in chapter VI. Use of sensor to detetct to S deficiency has been elaborated in VII and overall conclusion of the thesis discussed in last chapter (VIII).

1.1. Literature Cited

Araus, J.L. 1996. Integrated physiological criteria associated with yield potential. p. 150-166. In M.P. Reynolds, S. Rajaram, and A. McNab (eds) Increasing yield potential in wheat: Breaking the barriers. Mexico, D.F.: CIMMYT.

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

CAST. 1999. Gulf of Mexico hypoxia: Land and sea interactions. Task Force Report No. 134. Council for Agricultural Science and Technology, Ames, IA.

Rabalais, N.N., R.E. Turner, W.J. Wiseman, and D.F. Jr, Boesch. 1991. A brief summary of hypoxia on the northern Gulf of Mexico continental shelf: 1985-1988. In: Tyson RV, Pearson TH (eds) Modern and ancient continental shelf anoxia. Geo- logical Society Special Publication No.58, London, p 35-47.

Scharf, P.C., J.P. Schmidt, N.R. Kitchen, K.A. Sudduth, S.Y. Hong, J.A. Lory, and J.G. Davis 2002. Remote sensing for nitrogen management. J. Soil Water Conserv. 57:518–524.

Schilling, K.E. 2002. Chemical transport from paired agricultural and restored prairie watersheds. J. Environ. Qual. 31:1184-1193.

Steinheimer, T.R., K.D. Scoggin, and L.A. Kramer. 1998. Agricultural chemical movement through a field size watershed in Iowa: Surface hydrology and nitrate losses in discharge. Environ. Sci. Technol. 32:1048-1052.

Turner, R.E., and N.N. Rabalais. 1991. Changes in the Mississippi River water quality this century-Implications for coastal food webs. Bio. Sci 41:140-147.

USDA-NASS. 2008-12. http://www.ers.usda.gov/Data/FertilizerUse/ http://www.nass.usda.gov/census/census02/volume1/ne/st31_1_033_033.pdf

CHAPTER II. LITERATURE REVIEW

2.1. Low Nitrogen Use Efficiency for Current N Management

Nitrogen use efficiency (NUE) for world cereal production is low with estimates averaging 33% of fertilized nitrogen (N) recovered by the crop (Raun and Johnson, 1999). The primary cause of N loss is through nitrate leaching or denitrification from excessive rainfall. Current USA Corn Belt region N fertilizer management practices result in N losses to ground and surface water (Schilling, 2002; Steinheimer et al., 1998; CAST, 1999).

Low NUE of present N management practices is partly due to the poor synchrony between the N application and crop demand (Fageria and Baligar, 2005; Cassman et al., 2002; Raun and Johnson, 1999). Large preplant N applications cause poor synchronization. For example, an average N application in Corn Belt Region of the USA during the past twenty years is approximately 150 kg ha^{-1} (USDA statistics, 2003) with 75% of the applications made prior to planting (including the previous fall) (Cassman et al., 2002). During the first three weeks following emergence, corn uses soil mineral N at the rate of less than 0.5 kg ha^{-1} day^{-1}. However, after the first three weeks the corn plant takes up exponentially more N until tasseling, with an average of 3.7 kg ha^{-1} day^{-1} (Andrade et al., 1996) with the highest daily uptake of 6 kg ha^{-1} day^{-1} (J.S. Schepers, personal communication).

Depending on soil and weather conditions, preplant N could leach below the crop rooting zone early in the season before peak N uptake (Schroder et al., 2000). Total N taken up by corn by the silking stage is about 60% of total N accumulated during the growing season (Andrade et al., 1996; Aldrich and Leng, 1974). Therefore, large preplant N applications result into high levels of available N in the soil profile before actual active plant uptake, which is at risk of loss over several weeks.

The efficiency of a single pre-plant N application decreases with the rate of N fertilizer applied (Reddy and Reddy, 1993). In contrast, in-season N application results in improved NUE as compared to pre-plant N application (Olson et al., 1986; Miller et al., 1975; Welch et al., 1971). Keeney (1982) suggested that supplying N as the crop requires it could increase NUE.

Although there is sufficient research published to support improved NUE application strategies, farmer adoption of in-season N application in the USA corn growing regions remains low (Raun et al., 2001). Reasons for this low adoption rate have been suggested to be cost and practical considerations of equipment and labor (Cassman et al., 2002).

Another factor that contributes to low NUE is uniform N application rates to spatially and/or temporarily variable landscapes, even though several studies have shown economic and environmental reasons for spatially variable N applications (Lambert et al., 2006; Scharf et al., 2005; Shahandeh et al., 2005; Hurley et al., 2004; Koch et al., 2004; Mamo et al., 2003). Soil N supplies, crop N uptake, and N responses differ spatially within fields (Inman et al., 2005). Consequently, large amounts of N applied as pre-plant into the field at a uniform rate is at risk for environmental loss in areas of over-application or in soils at risk for loss. Another reason for low NUE is outdated N recommendations that promote over-application of N.

The recommended rate of N applied to corn in North Dakota currently depends on yield expectations, soil test nitrate analysis before planting (Stanford and Legg, 1984; Meisinger and Randall, 1991), crops that typically have N benefit if corn follows them in the rotation, and recent use of manure (Mulvaney et al., 2005). Several studies demonstrate N loss between 30-60% (Bock, 1984) but it could exceed up to 70% (Pierce and Rice, 1988).

The current North Dakota N recommendation excludes farmer experiences, regional climate, and cultural practices. Regional climate, including temperature and precipitation affect the availability of N to corn and the mineralization rate of residues and organic matter. Soils within a field also have varying characteristics (texture, pH, and organic matter content) that affect N loss through enabling leaching or denitrification in years of excessive rainfall and N mineralization rate. Ideally, the N added during a given growing season would be equally climate-sensitive and site-specific (Meisinger, 1984; Meisinger et al., 1992).

Estimation of crop biomass yield is sometimes used for N rate determination with C4 plants. For example, corn requires less N for a given amount of biomass compared to C3 plants such as wheat (Gastal and Lemaire, 2002). Predicting crop yield is nearly impossible due to annual variation in precipitation and pollination period temperature, particularly in dryland cultivation. Various methods have been considered for trying to improve estimation of target yield. Yields may be averaged over a number of years to obtain a mean yield that is then used to calculate N rate application, but while it reflects past yield, it is not an adequate predictor of future yields

Another technique for estimating target yield is to consider the yield results of recent years with favorable crop growing conditions. However, in years with poor growing conditions, N remains in the soil, or is lost during the non-crop growing portion of the year. Target yield prediction has been suggested as mean yield from the most recent five to seven years, with an additional 5 to 10% yield addition as ‘insurance’ against underfertilization (Rice and Havlin, 1994). Many surveys have reported that most of the producers overestimate the target yield to determine the N requirement (Goos and Prunty, 1990; Schepers and Mosier, 1991). Historical low cost of N fertilizer has encouraged producers to apply N at excessive rates so that N would not be a limiting factor for crop growth.

Lory and Scharf (2003) have identified problems with a yield-based N recommendation approach. In their study, 298 experiment locations in five states (USA) were used to evaluate the yield response to N application. The study showed that N recommendation as determined by the actual yield exceeds the economic optimum N rate (EONR) by an average of 90 kg ha^{-1}. The N recommendation was not correlated with the EONR and therefore, the yield expectation method was not a reliable tool for N recommendation because in many cases it overestimated the value of N application.

Similarly, studies in Wisconsin (Vanotti and Bundy, 1994; Bundy, 2000), Pennsylvania (Fox and Piekielek, 1995), and Ontario (Kachanoski et al., 1996) have shown the problems of using yield expectation to predict N rate and consequently raise a concern over its reliability and use for future N recommendations. Farmers and research scientists still use the yield expectation approach for N rate recommendation in spite of the finding that yield is poorly related to the N requirement of the crop.

Climate and crop management practices influence the yield production of all crops. In irrigated systems, growing degree days and temperature can be used to determine the yield potential of any given crop during the growing season. In a dry-land agriculture system, the amount of rainfall and landscape distribution plays major roles in determining yield potential. It is neither possible nor economical to remove all the limiting factors of crop growth, such as weeds, insects, and disease problems. Variation in rainfall and temperature can result in higher or lower yield than that predicted by yield potential goal.

The best N application rate for any single location within a field is the amount of N needed to optimize profitability for the farmer. Fertilizer N applied at the EONR would minimize N loss and its associated environmental problems; however, the timing of the N rate is also important to achieve greatest N fertilizer efficiency.

This study will examine the use of several precision agriculture tools and/or techniques such as on-the-go soil and crop sensors, which have the capability to sense soil N supply and crop N status and deliver spatially-variable N applications based on crop N requirement.

2.2. Soil and Plant Analysis

Soil and plant analysis is being used for N management of different crops. (Schroder et al., 2000). Current N management practices in the corn producing areas of the USA are based upon several soil analysis components. Some states include soil organic matter (Nebraska, North Dakota, Missouri and Minnesota), nitrate-nitrogen credit from the previous crop (Nebraska, Illinois, Iowa, North Dakota, South Dakota and Minnesota), yield goal (Nebraska, South Dakota and North Dakota), and N credit from nitrogen from manures and irrigation water (Dobermann and Cassman, 2002).

To supply the required amount of N with consideration of spatial variability, some studies (Franzen et al., 2002; Ferguson et al., 2003) have encouraged a soil-based approach of outlining spatial variable management zones (MZ) for variable N applications and improving NUE. Management zones are field areas with homogenous attributes in landscape and soil condition. Zones are considered homogenous when they have similar electrical conductivity (EC), crop yield, and producer-defined areas (Kitchen et al., 2003 Heiniger et al., 2003; Johnson et al., 2003; Flowers et al., 2005; Kitchen et al., 2005). Such attributes tend to have similar yield potential, input-use efficiency, and environmental impact from application of fertilizers.

Researchers suggest a variety of approaches for defining MZ boundaries. Geo-referenced data layers (i.e. soil color, electrical conductivity, yield, and topography) are statistically clustered or combined using geospatial statistical analyses within geographic information systems (GIS) to delineate zone boundaries (Schepers et al., 2004). Soil mapping units (Wibawa et al., 1993), remote sensing (Schepers et al., 2004; Franzen, 2004), topography (Franzen et al., 1998; Kravchenko et al., 2000), yield maps, and soil EC (Franzen, 2008) have been used successfully to delineate the MZ. Most of the delineation of MZ depends upon the sources that are static and less consistent because of the temporal variation on yield potential (Jaynes and Colvin, 1997; Ferguson et al., 2002; Eghball et al., 2003; Dobermann et al., 2003; Schepers et al. 2004; Lambert et al., 2006). Therefore, they might not be adequate alone to account for all of the variability of N requirement in a field.

Another approach is to use sensitive plants as indicators of the nutrient status of the soil. Some crops are good indicators of the overall growing conditions as they are directly link to the weather conditions and soil management practices (Inada, 1965). Usually, increased N availability in plants results more leaf N concentrations and thus more chlorophyll (Wolfe et al, 1988; Al-Abbas et al, 1974; Inada, 1965) and greater photosynthetic rate (Sinclair and Horie, 1989). The chlorophyll content of the corn leaf as estimated by the chlorophyll meter is highly correlated with corn yield and N concentration in the leaf (Schepers et al., 1992a).

2.3. Use of Tissue Analysis for N Management

Nitrogen concentration at critical states can be used as an indicator of crop N status. Critical N is the minimum amount of N required to produce maximum amount of growth at particular time (Ulrich, 1952). As a crop grows and develops, concentration of N is first high, and then decreases with maturity. The graphical representation of this progression is called the critical N dilution (Greenwood et al, 1990). The nitrogen nutrition index (NNI) is a ratio of the actual N in the plant to the critical N established by past experiments (Gastal and Lemaire, 2002, Lemaire et al., 1997). The value of NNI more or less than 1 relates to a non-limiting growth or deficient situation of the crop, respectively. The NNI approach has been used in wheat (*Triticum aestivum* L.) (Justes et al., 1994), grain sorghum (*Sorghum bicolor* L.) (van Oosterom et al., 2001), rice (*Oryza sativa* L.; Sheehy et al., 1998), rapeseed (*Brassica napus* L.); Colnenne et al., 1998), and grasses (Lemaire and Salette, 1984).

In corn, the approach of critical N at the early growth stage does not provide a reliable estimate crop N status (Binford et al, 1992a). Plenet and Lemaire (1999) suggested that this was because of competition between corn plants. The concentration of N decreases with increase in crop biomass, sometimes referred to as 'dilution' (Plenet and Lemaire, 1999). Herrmann and Taube (2004) found that the critical N dilution curve range for corn could be useful up to the silage maturity. The concept of critical N may be more practical in small-scale agricultural systems, but it is usually not practical in large-scale commercial agriculture.

2.4. Spatial Variation

Commercial corn production fields can be categorized by differences in soils, production history, soil management techniques, movement of water and nutrients that imposing spatial variability. These spatial differences cause differences in plant N requirement, susceptibility to stress, and variation in plant productivity across a landscape. Variations in slope within a landscape can have a large impact on grain yield variability (Jiang et al., 2004; Kravchenko et al., 2005; Kravchenko et al., 2000). Soil depth and drainage also have a large impact on corn grain yield (Timlin et al., 1998). In commercial corn production, higher N fertility levels have been observed in footslopes and depressions due to the flow of water and soil deposition of clay and organic matter to these landscape positions. This effect is most evident in soils with upper landscape positions that are low in organic matter (Jiang et al., 2004; Kravchenko et al., 2000). Phosphorus and potassium concentrations also tend to have higher levels of plant availability in footslopes and depressions, although higher crop removal with higher crop production history may produce lower

P and K levels than expected (Kravchenko et al., 2000). The deposition and distribution of P and K may therefore not be as correlated with slope as is organic matter (Kravchenko et al., 2000).

Topography is an important factor explaining spatial variation in grain yield. Topography and slope helped to explain 30-85% variability in the yield of corn and soybean (*Glycine max* L.) cropping systems, respectively, (Jiang et al., 2004). Although topography and soil properties offer some understanding of variability in grain yield, but they are only two factor of many that contribute to variability

Crop stress results in a reduction of growth and yield. Crops are influenced by seasonal weather conditions under variable landscapes. During a dry growing season or a wet growing season, differences in yield due to landscape position are magnified Landscapes having high organic matter and water holding capacity are generally less affected by drought conditions as compared to the upland areas (Kravchenko et al., 2005; Timlin et al., 1998). Greater rainfall can cause yield decreases in depressions, where ponding can occur (Ginting et al., 2003). Decrease in soil organic matter and moisture because of structural degradation can result in stress, which intensifies spatial differences.

Tillage and management practices across a landscape also influence plant growth and productivity. Increases in spatial variability have been observed in regions where reduced tillage and/or reduced chemical dependence were used (Kravchenko et al., 2005; Ginting et al., 2003).

2.5. Fertilizer Placement and Timing

Nitrogen is a crop nutrient that is commonly applied as fertilizer, and it is susceptible to many soil transformations. These transformations occur at the soil surface and within the soil and the transformations can influence NUE. Leaching, runoff, and volatilization are important loss avenues for N.

There is need of N application in ways that ensure a high level of N availability to the crop with high NUE. Broadcasting UAN (urea-ammonium nitrate solutions) results in lower yields than injected UAN, particularly on fields with surface residue (Fox et al., 1986; Maddux et al., 1984; Mengel et al., 1982; Bandel et al., 1980). Loss of N using broadcast UAN includes volatilization of ammonia from the urea part of the solution and immobilization of N in the surface residue (Bandel et al., 1980). Therefore, fertilizer placement below the soil surface may often be more effective.

In modern corn hybrids, approximately 15% of the total N uptake and 5% of the total dry matter accumulation occurred by the V7 growth stage (Shanahan et al., 2007). By silking, 60% of total N uptake has taken place and 40% of total dry matter has accumulated. Therefore, a considerable amount, around 40%, of the crop's total N uptake occurs during a 30 days period between V7 and VT. There are opportunities to improve N synchronization by delaying in-season N applications until V7 without compromising with yield (Holland and Schepers, 2010).

Scharf et al. (2002) conducted an experiment at 28 locations and over a variety of soils where timing of N fertilizer was the experimental variable. A single application of ammonium nitrate was applied at a rate of 180 kg N ha^{-1} at: 1) planting, 2) V7, 3) V14, or 4) silking stage. Corn yield responded positively to N fertilizer at the majority of locations. When all 28 trials were considered, there was little yield reduction with N applications delayed as late as V14. Climate might affect the relative risk of yield loss with delayed N application. In a dry year, for many locations, maximum yield was attained on water stressed corn by surface applying N as late as V14. A complication with this study is that many of the locations had been amended with animal manure; many others had soybean as a previous crop, and a number of different tillage systems were combined across the entire experiment. There were two non-manured locations under corn after corn, though both were tilled. Previous crop, manure management, and tillage management are known to affect N mineralization rates, soil-N supply and therefore, the seriousness and timing of N deficiency.

Contrary to the general conclusions in Scharf et al. (2002), one of the sites experienced irreversible yield loss when N was applied on or after V6, which means that N availability at this site must be adequate prior to side-dressing to ensure that maximum yield is obtained. As the level of N deficiency increased, the grain yield response to N decreased with greater delay in the side-dress N application, meaning that there was a positive interaction between the level of N deficiency and the time of N application on corn yield.

Binder et al. (2000) examined N fertilizer timing in Nebraska on silty clay loam soil under double-disc tillage. The previous crop was sorghum for the first year and fallow for the second. Side-dress N at V8-V10 was one of the best ways of supplying N to corn. Soil N status affected how late the N application could be delayed without causing a yield reduction. Therefore, optimum N application time depends on the degree of N deficiency, which is related to both available soil N and the crop N demand. This was particularly true in the first year of this research, where the climate caused more severe N stress than in the second year. In year one, for the 0 kg N ha^{-1} N rate, N had to be applied prior to V6 to attain maximum yield, due to dry soils later in the season. In the second year with more soil moisture, the application at V16 resulted in similar yield as applications earlier in the season.

2.6. Leaf Area Index

Leaf Area Index (LAI) is defined as the ratio of leaf surface area to ground surface area (Cowling & Field, 2003). Leaf area index is a direct representation of the photosynthetic capacity of the vegetation (Whittaker & Marks, 1975). For some species/communities, LAI may be directly related to vegetation productivity, but for others, the relation of LAI to productivity depends on other variables such as light, canopy extinction coefficient, NUE's, and amount of light intercepted at the top of the canopy (Anten, et al., 1995). For example, C4 plants have higher NUE, when grown in dense stands, C4 plants produce more leaf area than C3 plants grown under the same environmental conditions (Anten, et al., 1995).

Several approaches have been developed to estimate LAI from remote sensing. The most commonly used are inversions of canopy radiative transfer models (Fang et al., 2003; Knyazikhin et al, 1999; Weiss & Baret, 1999) and empirical relationships between LAI and spectral vegetation indices (Chen & Cihlar, 1995; Curran, 1983; Jordan, 1969; Myneni et al., 1997b; Wiegand et al., 1979). A short-coming of algorithms based on vegetation indices is the difficulty in extrapolating their results to larger regions or to different canopy types (Curran, 1983). Vegetation index predications are often confounded with atmospheric and background effects, canopy architecture, solar-target-sensor geometry and to lack of spectrum differences when measuring moderate to high levels of LAI (Fang et al., 2003).

2.7. Environmental Interaction

Crop productivity is affected by environmental stress. Boyer (1982) found that unfavorable environmental conditions could reduce corn yields by more than 70%. Modern breeding programs have produced corn hybrids that are able to tolerate greater plant densities and environmental stresses (Meghji et al., 1983; Tollenaar, 1989); however genetic improvements only account for about half the yield increase realized in the modern breeding era (Boyer, 1982). The remaining gains can be attributed to improved management practices.

Fulton (1970) found that once available soil moisture at 40 cm in soil depth dropped below 25%, corn yield was severely reduced. In several experiments, application of irrigation water doubled yield. Drought stress at silking results in barren ears (Herrero et al., 1980). Drought stress after silking can reduce crop yield by 20% (Dwyer et al., 1992). Decrease in stem elongation, cob length, leaf area, and grain yield can be expected due to moisture stress (Denmead et al., 1960). In another study, low soil moisture before silking reduced grain yield by 25% whereas moisture stress at silking resulted in reduced grain yield by 50% (Denmead et al., 1960). Additionally low soil water availability after silking reduced yield by 21% (Denmead et al., 1960).

High temperatures can result in crop stress. When temperatures increase to 45 °C, the rate of photosynthesis may be inhibited in corn by as much as 95% (Crafts-Brandner et al., 2002). Heat stress in corn could result in delay of tassel initiation Crafts-Brandner et al., 2002). Increase in air temperature in wheat (*Triticum aestivum* L.) from moderate (22/17°C) to high (32/27°C) decreased the photosynthetic rate and total biomass production by 11 and 32%, respectively (Al-Khatib et al., 1990). Moisture stress can reduce net photosynthesis in corn by 25% when leaf water potentials reach -16 kilopascals (Boyer, 1970). In cotton, increased photosynthetic rate was consistently associated with higher rates of application, which resulted in higher yield (Bondada et al., 1996).

Jacobs et al. (1991) observed decreases in plant productivity, grain bearing ears, number of kernels per ear, and kernel dry weight with increase in plant population. Grain yield increased with greater population due to the number of total ears, regardless of individual plant production. However, when restrictions were put on available N, a 65% reduction in yield was observed. High plant populations also delayed silking with reduced N, which resulted in reduced pollination (Jacobs et al., 1991). Inadequate fertility can increase stress in a developing corn plants (Eck, 1984). Multiple studies have shown reductions in growth and productivity due to inadequate levels of N (Eck, 1984; Jacobs et al., 1991).

2.8. Spectral Response

Environmental stresses result in leaf spectral property changes. Carter (1993) observed similar changes in spectral responses across multiple species with changes in plant competition, disease interaction, insufficient ectomycorrhizal infection, senescence, herbicide damage, increased ozone, dehydration, and presence of saline soils. The basis for these responses was that stress reduces chlorophyll content. Chlorophyll *a* has relatively low absorbency in the green and red spectrums. Even small changes in chlorophyll concentration can cause increased reflection at these wavelengths (Carter et al., 2001). Zhao et al. (2003) found more than a 60% reduction in chlorophyll *a* in leaves after 42 days of emergence, resulting in increased reflectance near 550 and 710 nm.

Micronutrient deficiencies could also induce stress similar to N deficiency. Masoni et al. (1996) after evaluating Fe, S, Mg, and Mn deficiencies in corn found that leaf chlorophyll concentrations decreased with decreasing micronutrient concentrations. Chlorophyll *a* concentration was 22% less when Fe, Mg, and Mn were deficient compared to unstressed plants. Sulfur deficiency resulted in a 50% reduction in chlorophyll *a* concentration. The reduced chlorophyll concentrations resulted in decreased light absorbency and increased reflectance near 555 and 700 nm (Masoni et al., 1996).

2.9. Use of Spectral Properties of Plants

The total amount of solar energy absorbed by the leaf surface is directly linked to the total photosynthetic pigment present in the leaf (Gates et al., 1964). Photosynthetic potential of plant is directly related to chlorophyll content (Hatfield et al., 2008). Total chlorophyll content changes in response to plant developmental stage or stress. So measuring chlorophyll content can be a tool for evaluating the physiological health of a plant. Gitelson et al. (1997) evaluated the vegetative indices of multiple species and determined that reflectance and absorption of light in the 530-630 nm and near 700 nm wavelengths were related to chlorophyll content. Light reflectance of plant tissue at the specific wavelengths of 700 and 550 nm were highly correlated with chlorophyll content (r^2 > 0.97). Wavelengths in the near infrared spectrum (750-900nm) were relatively insensitive to chlorophyll content. An index was established for predictive measurements using the ratio of the 750 nm light reflectance to the 550 nm wavelength (Gitelson et al., 1997). A similar study was conducted on corn (Ciganda et al., 2009). Individual leaves were sampled every two weeks. The red-edge wavelength (average reflectance in the range from 720 to 730nm) was used to estimate total chlorophyll content (r^2 > 0.94).

Crop reflectance is defined as the ratio of amount of incident light as denominator to the amount of light reflected back as numerator (Shroder et al., 2000). Raun et al. (2001, 2002) used active optical sensors for in-season N management in winter wheat fields. Within their approach they divided NDVI by growing degree days accumulated from planting until sensing, defining this value as the in-season estimate of yield (INSEY) and was related to the growth rate of the plant. The INSEY is a more robust indicator of plant health compared to the sensor reading alone (Raun et al., 2001). If using the instrument reading alone, the reading must be taken at exactly the same growth stage in subsequent years for the relationship to be valid. The INSEY normalizes the reading for time differences between seasons, resulting in better relationships for readings taken within year and between years.

The penetration of light into the leaf is greater in the green and red-edge spectra than blue and red. During photosynthesis, more than 80% of incident light absorption was observed in the regions of 400 to 700 nm (Moss et al., 1952). Consequently, light in the green and red-edge spectra would be more sensitive to changes in chlorophyll content than other wavelengths because the absorption coefficient in these spectra provide a range of values, rather than a high narrow range of values, called saturation (Gitelson et al., 2003). Absorbance in the visible spectrum by leaves of several plant species increased with changes from lighter green to darker green tint (Gates et al., 1964). Maximum chlorophyll absorbance occurred at 680 nm whereas the minimum was established at 550 nm. The angle of incident light on the leaf also affected the radiation absorption.

The most common method of spectral plant analysis is comparing the amount of red light to near infrared light absorbed beneath a plant canopy to that above the canopy (Federer et al., 1966). As LAI increases, the amount of light absorbed in red spectrum and light reflected in the near-infrared (Federer et al., 1966) increases.

Jordan (1969) established that by using a light ratio (675/800 nm) beneath the forest canopy rather than above, LAI could be determined indirectly. The authors also concluded that while LAI could be estimated remotely, environmental conditions such as cloud cover and angle of incident sunlight could greatly affect the accuracy of measurements. Similar approaches have been utilized in evaluating grass canopies (Tucker, 1979). With increasing green biomass, incident light in red spectra (630-690 nm) is increasingly absorbed. Irradiance near the infrared spectrum is defined as lack of absorption, or reflection by chlorophyll (Tucker, 1979). Several ratios of red and near infrared spectrum are related to mass of plant greenness (Tucker, 1979).

Several ratios are collectively known as vegetative indices, which are sensitive to different environmental and physiological parameters. Common spectral vegetative indices include: chlorophyll indices (Clgreen = (RNIR/Rgreen)-1) for estimating chlorophyll content (Gitelson et al., 2005), and the soil adjusted vegetation index (SAVI = (RNIRRred) (I+L)/(RNIR+Rred+L)) for LAI estimation (Huete, 1988). The normalized difference vegetative index (NDVI) is a widely used vegetative index (Raun et al., 2001).

The plant pigments that are most involved in the photosynthetic process are chlorophylls a and b, which absorb light in red and blue spectra and reflect green (Slaton et al., 2001). There is more reflectance in the near infrared (700-1400nm) spectrum of light (Slaton et al., 2001; Gausman 1977; Gausman, 1974). This property of plant leaves being used to dtect the nutrient defficnecyies and bimass measurement (Osborne et al., 2002). The Normalized Difference Vegetation Index (NDVI), is the most used vegetative index by researchers and practitioners for plant biomass prediction (Blackmer et al., 1996a; Stone et al., 1996; Osborne et al., 2002). NDVI is ratio of in the red wavelength to NIR light. (Deering et al, 1975):

NDVI = (NIR–red) / (NIR+red) (Eq. 1)

Where,

"NIR" is the reflectance in the near infrared region of the spectrum and

"red" is the reflectance in the red region of the spectrum.

(Gitelson et al., 1996)

The NDVI gained wide acceptance with researchers due to its ease of calculation and its use of two light spectrum (Deering, 1978). The NDVI has been related to N status of the leaves, chlorophyll content, green leaf biomass, and grain yield (Shanahan et al., 2003; Ma et al., 1996; Solari et al., 2008; Shanahan et al., 2001). However, NDVI has some limitations including saturation (absorption of all the light in visible spectrum results in NDVI value close to 1) at high green biomass and is not useful by itself in predicting yield (Gitelson et al., 1996; Miyneni et al, 1997). The red wavelengths produces a flat response after LAI increased to a value greater than 2, whereas the near infrared reflection continues to respond even at LAI ranges from 2-6 (Gitelson et al., 1997). To overcome this limitation, Gitelson et al. in 2004, proposed that by multiplying the

NDVI by a coefficient “a”, the relationship between the crop biomass and crop reflectance might improve. This formula was called the Wide Dynamic Range Vegetative Index (WDRVI):

$$(a * \rho NIR - \rho red)/(a * \rho NIR + \rho red) \qquad \text{(Eq. 2)}$$

Where,

Coefficient *a* is in the range of 0-1. When a is 1, the Eq. 2 is Eq. 1.

The development of active sensors has made sampling relatively insensitive to changes in ambient light and environmental constraints. Active sensors contain modulated light emitting diodes that emit light at specific wavelengths in a specific pulsing sequence onto a canopy (Shaver et al., 2010). The sensor measures the amount of light emitted by the instrument and reflected in the same pulse sequence rather than ambient sunlight (Shaver et al., 2010).

2.10. Estimation of Vegetative Indexes

2.10.1. Nutrient status

Soil fertility affects corn growth, and nutrient deficiencies can be corrected with the application of fertilizers (Belay et al., 2002). Numerous techniques have been used, including soil testing and destructive plant analysis, to determine plant nutrient status. Most recently, the use of non-destructive sensors have been used to determine plant nutrient status (Ma et al., 1996; Solari et al., 2008; Mistele et al., 2008). Most of the sensor work has been devoted to crop N status (Wolfe et al., 1988).

Nitrogen deficiency reduces the photosynthetic rate of leaves. Corn production is often reduced due to low N availability producing lower kernel dry weight and general reduction in all components of corn yield (Gentry et al., 1993). Selection of wavelengths relevant to corn N status is critical to determining corn N status (Belay et al., 2002; Gentry et al., 1993; Wolfe et al., 1988).

Shanahan et al. (2003) proposed using NDVI and Green NDVI (GNDVI). In the GNDVI, the two spectrum used were NIR and the other was in the range of 500-600nm. The light in this spectrum is green thererefore; it was named as green NDVI. The basis for their finding was an experiment on four corn hybrids under irrigation using five nitrogen rates. Active-optical sensors emitted light in four bands: blue (460 nm), green (555 nm), red (680 nm), and NIR (800 nm). Differences in NDVI were related to N rate and sampling date. Nitrogen treatment was correlated to increased chlorophyll content ($r^2 \geq 0.96$). In addition, Hansen et al. (2003) found that NDVI could be used successfully in evaluating growth and development of small grains.

2.10.2. Yield estimation

Despite the establishment of a relationship between vegetative indices and green leaf biomass, Gitelson et al., (2003) found the use of sensors in yield estimation difficult.

In wheat, sensor readings at Feekes growth stage 5 tended to be more correlated with grain yield than any other stage of development (Moges et al., 2004). Raun et al. (2001) found that sensor based estimated grain yields were able to explain 83% of grain yield variability. The relationship between sensor reading and yield may be variable over space and time (Inman et al., 2007). The inconsistencies in estimating yield have included sampling date, hybrid variation, seasonal changes, spatial differences, and N fertilization (Shanahan et al., 2001; Inman et al., 2007).

2.11. Nitrogen Management Using Site-Specific Technologies

Remote sensing measures information from an object or area without being destructive. Examples of remote sensors include ground-based active-optical sensors, satellites imagery, aerial imagery or photography, ground-based reflective sensors and leaf chlorophyll sensors (Printer et al., 2003; Hatfield et al., 2008). Remote sensing has been used in agriculture for estimating land use, land cover, and crop biomass (Henebry et al., 2005; Kogan et al., 2004; Sala et al., 2000;

Deering et al., 1975). Remote sensing techniques are now utilized to determine the spatial crop N status in-season (Osborne et al., 2002). Several studies have resulted in development of the relationship between chlorophyll content, crop N status, and spectral reflectance (Blackmer et al., 1996a; Stone et al., 1996; Bausch and Duke, 1996; Osborne et al., 2002). Some of the first studies to utilize remote sensing techniques investigated the SPAD® (Konica-Minota Americas, Ramsey, NJ) chlorophyll meter, canopy reflectance or color photography (Schepers et al., 1992b; Blackmer et al., 1993; Blackmer et al., 1994; Blackmer and Schepers, 1996; Schepers et al., 1996; Blackmer et al., 1996a; Blackmer et al., 1996b).

Since the mid-1990s, a variety of geospatial technologies have been available to the agricultural market. Crop reflectance, color photography, and GBAO sensors have been successfully used to measure spatial variability in crop canopies (Blackmer et al., 1993; Schepers et al., 1992; Blackmer et al., 1994; Blackmer and Schepers, 1996; Schepers et al., 1996; Blackmer et al., 1996a; Blackmer et al., 1996b).

2.12. Use of Sensors and NDVI

Most farmers apply N with consideration of previous crop, soil drainage and soil management, but they do not generally use in-season tools for diagnosing an optimal N rate (Kitchen et al., 2001). Farmers also tend to apply higher rates of N fertilizer than recommended to ensure maximum yield (Scharf et al., 2006). Excessive N rates for the yield attained often results in unused N moving to ground and surface water in the form of nitrate (Scharf et al., 2006). Use of proximal plant canopy sensors offers an opportunity for corn producers to adjust N requirement according to the crop requirement.

Determining the best N rate for a field and variety of corn is difficult. The concept of ‘need basis‘ using sensing tools was proposed by Schepers et al. (1995) to aid in reducing environmental contamination from excess nitrate in corn production. This approach used the SPAD chlorophyll meter measurements, which helped estimate the crop N status against a standard color and then applying N as required. This technique helped to maintain the optimum yield with less fertilizer application (Varvel et al 1997). The weakness of this approach was the need to physically gather tedious readings from many leaves and standardize the N sufficient plants from N deficient within multiple varieties.

The SPAD chlorophyll meter is an active optical sensor that measures transmitted light through the plant leaf at two different wavelengths, one in the near-infrared (NIR) and one in the red (RED) region of the light spectrum, and computes a value which is determined by the manufacturer. The meter is a non-destructive technology that helps to analyze leaf tissue for the assessment of the N status/nutrition of the plant. Studies showed that chlorophyll meter readings have positively correlated with chlorophyll content (Schepers et al., 1992). The SPAD meter, however, is placed onto one single leaf per measurement, which makes multiple readings in a field time-consuming.

Chlorophyll meter research on corn has focused on segregating locations with positive response to N fertilizer from locations with low response potential, to indicate if and when N supplementation is needed (Scharf et al., 2006). Corn hybrid characteristics confound chlorophyll meter calibration and reduce the instruments effectiveness in predicting N availability across large regions (Bullock and Anderson, 1998; Schepers et al., 1992). However, it is easy to normalize the meter data for a specific hybrid as well as growth stage, against a high-N nutrition control. If properly calibrated in many hybrids, the instrument would be better able to permit comparisons across locations and growth stages. Commercial application of chlorophyll meter requires a reference strip, which is usually an adequately N-fertilized area within the field under local growing conditions (Schepers et al., 1992).

Bullock and Anderson (1998) found no correlation between chlorophyll meter readings and yield at the V7 stage. However, at advanced stages (R1 and R4) they detemined a better correlation between leaf N concentration and yield. At advanced stages (R1 and R4), the meter readings were related more to the grain yield than leaf N. The correlations coefficient between the meter readings and leaf N was positive at early stages (r^2=0.23) and decreased in value as growth advanced (r^2=0.20). Scharf (2001) found that absolute rather than comparative chlorophyll meter readings taken at V6 were related strongly to the economically optimal nitrogen rate (EONR) and recommended lower N rates than used by producers in the same fields. Although the meter N rate recommendation did not increase crop profitability, but profitability was mainatained when compared with producer chosen N rates. In contrast, Bullock and Anderson, 1998 concluded that absolute readings of chlorophyll meter could not be used for accurate N predictions in wheat.

Successful N recommendations have been developed in irrigated corn using relative chlorophyll meter readings (comparison of sensor readings between high N plot and normal farmer field), where irrigation water was used as an N delivery system. By continually checking corn N status with the meter, a low rate of N could be applied whenever meter readings fell below a critical value (Shapiro, 1999; Varvel et al., 1997). An area with a non-limiting N rate applied was required to produce the relative chlorophyll meter recommendations.

Scharf et al. (2006) found that relative chlorophyll meter readings better predicted corn grain yield than absolute meter readings. In dryland corn production systems, where the opportunity to make corrective N applications is restricted to one application, there is not an absolute relationship between chlorophyll meter readings and the N rate needed by the crop(Scharf et al., 2006). In contrast to irrigated systems where fixed low N rates can be applied repeatedly as needed, in dryland systems the chlorophyll meter will only be useful in guiding N application rates if the meter can be the basis for that single corrective N rate recommendation (Scharf et al., 2006).

Corn growers may benefit from a system that would convert reflectance measurements from vehicle-mounted sensors directly into an N application rate (Scharf and Lory, 2009). Ground-based active-optical (GBAO) sensors have been successfully used in winter wheat N management in Nebraska (Raun et Al., 2002). They can be used at any growth stage of crop, depending on their light source, without consideration of clouds and ambient light. The GBAO sensors emit coded light of specific wavelengths onto the crop foliage. The modulated light pulses of specific duration of each pulses, which when the pulses are sensed in the same pattern and the light reflected back to the instrument. The modulation works in the same principle as in an infrared remote television controller. The light that is reflected back to the sensor in the same pulse code is recorded by the instrument. In a GBAO sensor using red and infrared light, the red NDVI is related to percent biomass, which in turn is related to predicted crop yield. Differences between a known high-N yield within the field and yield predicted from normal field can be used to predict the N required to increase the productivity of the area with lower yield prediction to the yield production of the high-N area.

Solari et al. (2008) studied the potential use of active optical sensors at the field scale in determining N status in irrigated corn. Differing N rates and time of application were used to induce variable growth. Two vegetative indices were evaluated; NDVI at 590 nm and chloropyll index (CI) at 590 nm. Both indices were related to N rate, hybrid, and growth stage. Sensor readings were more related to chlorophyll content at vegetative growth stages than reproductive stages.

Several studies have been conducted to measure the efficacy of two commercially available active optical sensors, GS Model 505 (Trimble, Inc., Sunnyvale, CA), and CC ACS-210™ (Holland Scientific, Inc., Lincoln, NE) in predicting corn yield. The basic differences between the two sensors are the use of different wavelengths to calculate NDVI. While both sensors use wavelengths in the visible and near infrared spectrums, the GS Model 505 works with reflectance measurements from 660 nm and 770 nm whereas the CC ACS-210 emits and detects light at 590 nm and 880 nm. Both sensors are sensitive to crop growth differences ($r^2 > 0.89$). However, at later growth stages the GS Model 550 showed saturation compared to the CC ACS-210 because in CC ACS-210 different wavelength used to predict yield, thus making it less sensitive and more usable even at the later growth stages (Shaver et al., 2011). Additionally, GS was sensitive to row spacing and sensor speed (Shaver et al., 2011). In contrast, CC ACS-210 was found stable over early and late growth stages as well as across multiple row spacing's and sensor movement speeds (Shaver et al., 2010). Therefore, while choosing an appropriate sensor variable N management, the red-edge (680-730nm) or/and green wavelength (590nm) provides a better estimation of canopy development (Shaver et al., 2010; Shaver et al., 2011).

The hand-held GS 505 is also a GBAO sensor, which, unlike the chlorophyll meter, measures reflected light. The GS has important advantages over the chlorophyll meter, satellite images and aerial photographs in managing corn N nutrition at a field scale including that it is faster and less labor intensive than the chlorophyll meter. The GS also does not require full canopy or ultra-high resolution as do aerial photographs (Scharf and Lory, 2002; Sripada et al., 2005).

The GS is an 'active proximal' sensor, not limited by cloud cover or diurnal variation and emits the light, which measured upon reflectance back to the sensor (Kitchen et al., 2010). The light emitted at two different wavelengths, red 670 nm and NIR 780 nm, have related mainly to canopy biomass and photosynthetic capacity (Kitchen et al., 2010). Reflected red radiation always negatively correlated with canopy photosynthetic activity, whereas the NIR reflectance always positively related to canopy biomass (Knipling, 1970).

Nitrogen deficient plants often exhibit higher levels of reflectance in the visible (400 – 700nm) portion of the spectra due to reduced photosynthetic activity, and lower reflectance levels in the NIR (>700nm) region explained by the reduced leaf surface area in the N-stressed plants (Daughtry et al., 2000). In addition, leaf tissue is known to reflect more NIR radiation than most soil surfaces (Daughtry et al., 2000). The GS instrument computes the NDVI as: (NIR780nm - RED670nm) / (NIR780nm + RED670nm). The NDVI readings were found to change temporally as a logarithmic function of the canopy biomass; but after canopy closure, the biomass can continue to increase after NDVI reaches a maximum (Gilabert et al., 1996). In other words, the NDVI becomes 'saturated' after canopy closure (Gilabert et al., 1996).

Raun et al. (2002) and Mullen et al. (2003) have shown that the GS NDVI value can be used to direct variable rate N applications to wheat and improve NUE. However, limitations to using of the GS during corn's in-season application window (V8 to R1) have been documented by Shanahan et al. (2008) whereas NDVI became saturated at intermediate LAI values, the greater corn vegetative biomass makes sensor use in the red spectrum difficult (Gitelson et al., 1996).

Clay et al. (2006), using the Cropscan® (Cropscan Inc., Rochester, MN) sensor, was able to determine the influence of water and N stress on corn canopy light reflectance. They found that the relationship between reflectance and N or water stress changed due to corn growth stage and the wavelength utilized. By V11 to VT, canopy closure was complete. Additional N resulted in an increase in the values of all spectral indices tested while reducing reflectance in all the bands except the NIR. This suggested a low sensitivity in the NIR with N nutrition.

A comparison between three N fertilizer models showed that at about V8, N fertilizer recommendations based on NDVI were more predictive than recommendations based on expected yield or soil water yield prediction (Clay et al., 2006). When corn was under water stress, the canopy reflectance was higher than non-stressed corn between V8 and VT (Clay et al., 2006). The reflectance values increaed over the visible spectral range under stressed corn canopy between V8 and VT growth stage; however, the change in reflectance was larger in the green spectra than in the other bands. Clay et al. (2006) concluded that green reflectance might be more sensitive to N stress than NIR, while red reflectance appeared to be more sensitive to water stress, as yield losses due to water stress correlated with reflectance in the green and red bands along with NDVI. Ultimately, they found that a green NDVI (GNDVI) index correlated better with corn grain yield than many other indices tested in the study. These conclusions have been supported by Shanahan et al. (2008).

The transformed soil adjusted vegetative index (TSAVI) was proposed as an alternative index to deal with the problem of the changing influence of soil variability in reflection of light when using a NDVI sensor. However, Shanahan et al. (2001) concluded that NDVI was superior to TSAVI in detecting corn canopy variation. Green NDVI, which substitutes the red within the NDVI equation with the green wavelengths, was proposed by Gitelson et al. (1996) to enhance the sensitivity of the NDVI, and was found by Shanahan et al. (2001) to better distinguish corn canopy differences. Martin et al. (2007) used the GS with the red NDVI to conduct a study where the progression in temporal NDVI of the growing corn canopy was measured, and the spatial variability of corn growth over time was evaluated using the coefficient of variation statistic (CV). Corn grain and biomass yields were best related to NDVI when readings were obtained between V8 and V12. They found that this complementary approach, using both average NDVI value and the CV for that value within corn growth stage was able to improve yield potential estimation compared to NDVI value alone.

Solari et al. (2008) used the chlorophyll meter (CM) and CC ACS 210 sensor to evaluate NDVI using the green spectra (590 nm) and computed a CI as CI590 = (NIR/VIS590) – 1. They also examined when the readings should be taken and which index better predicted corn grain yield. Greater r^2 values were achieved when readings were taken during vegetative growth than during reproductive stage. This indicated that the presence of the tassel confounded the relationship between the CM values and sensor NDVI and CI values. The authors suggested that this might be due to the reduced ability of the sensor light source to penetrate further than the 5th or 6th leaf into the corn canopy when the reading was taken at a height of around 80 cm above the canopy. They also found that CI values were more sensitive than GNDVI values in assessing crop N status. Although the two sensor measurements were equally sensitive in assessing yield potential, the authors suggested that the CI would have a greater potential for directing spatially variable in-season N applications.

Freeman et al. (2007), using the GS, performed by-plant measurements of NDVI and considered the possibility of complementing NDVI readings with plant height information for predicting corn forage yield and forage N uptake. He concluded that the best predictor of corn forage yield and N uptake was NDVI calculated alone at early stages (V7 to V9). Scharf and Lory (2009), using the Cropscan® MSR87 multispectral radiometer (Cropscan, Inc., Rochester, MN), conducted a study to calibrate reflectance measurements at V6 for prediction of the EONR for corn in Missouri. Many wavelengths were evaluated along with different sensor orientations. They found that best orientation of the sensor was facing downwards, with the sensor facing the crop canopy. They also reported that the proportion of soil captured in the sensor's field of view influenced reflectance measurements most with the downward orientation, suggesting that this soil interference may have aided in diagnosing soil N supply, due to the effects of N on plant size, soil cover, and soil contribution to the measured reflectance values. Their conclusions suggest that the relationship between reflectance and EONR might be different according to soil color.

Among the wavelengths evaluated by Scharf and Lory (2009), the different NIR bands had no effect on r^2 for the relationship, while selection of the band in the visible part of the spectrum significantly influenced r^2. Simple relationships between NIR and VIS bands were no different from those among the different NDVI indices. The EONR was somewhat better correlated with GNDVI (r^2=0.66) than with NDVI (r^2=0.55). The authors concluded that N savings using their calibrations could be anticipated only when pre-plant N rates were limited and the remaining N applied after crop establishment.

Kitchen et al. (2010), using a CC ACS-210 sensor, conducted a study to evaluate the use of active optical sensors to assess corn N need and derived N fertilizer application rates that would return maximum profit relative to the grower's use of a single application rate at planting. The GNDVI was used with a sufficiency index (SI), ratio of normal N plot and high N plot, in order to normalize the GNDVI measurements against a GNDVI for a well fertilized area within the field. Doing this also normalized the confounding effects of numerous management (e.g., hybrid) and environmental (e.g., soil and precipitation) factors within the field, focusing sensor management on the specific N needs of the crop. They found that the sensor recognized differences in crop N status between plots that received no N at planting and plots that received 67 kg N ha^{-1}. They observed that when too much N applied before sensing there was little or no difference in sensor values between corn from the well N fertilized reference and those where a response to later N application expected. When SI values were around 0.9, the analysis showed that another 50 to 125 kg N ha^{-1} was still needed to maximize profit. They explained this wide range in optimal N rates by noting that the crop was well fed with N at early growth stages, which is what the sensor “sees”, although later on, in advanced growth stages, the crop suffered an N shortage because at V12 the crop still requires substantial N to reach maturity and maximum yield potential. These findings highlight an important obstacle in using this technology to make an N diagnosis for season-long crop N needs using an early-season snapshot of crop N status. At side-dressing, even late side-dressing (V12), the crop still has time to reach physiological maturity, and many weather factors might influence yield between side-dressing and maturity, making the N need prediction difficult, particularly in southern states of the USA.

Kitchen et al., (2010) found a weak relationship between optimal yield and SI, but believed that the trend in the dataset could be used, empirically, to derive N application rates. On the other hand, their data suggested that the chlorophyll meter might be more effective in delineating subtle differences in crop N nutrition, as this instrument was able to “see” differences in N nutrition much earlier in the growing season. This was because the ground-based sensors, in considerable proportion, “see” the upper leaves of the canopy, whereas the chlorophyll meter was used on the last fully expanded leaf, which is more likely to show N deficiency. They concluded that understanding N source and fate of N within fields is complex and were not able to offer a solid system of ideas to explain why their results were not consistent.

Dellinger et al. (2008) examined the relationship between EONR and readings from the CC ACS-210 sensor and evaluated the potential for side-dress N recommendations. Their results suggested that the use of the GNDVI using this sensor would be limited to situations where there little or no N fertilizer was applied at planting. The EONR was correlated with the GNDVI when manure was applied at planting or when fertilizer was not applied at planting. However, when 56 kg N ha^{-1} applied at planting, the relationship between GNDVI and EONR was non-significant. They also found that a high N reference area at planting was needed for making side-dress N recommendations.

Raun et al., (2001 and 2002) developed methods for the use of a GBAO sensor to improve NUE in winter wheat. He utilized INSEY to relate GS red NDVI readings to wheat yield. The application of this methodology was effective because NDVI is a predictor of crop biomass accumulation and considers tiller mortality due to cold, dry winters (Deering et al., 1975; Stone et al., 1996) The relationships in Raun et al., (2001) and Lukina et al, (2001) figures showed that data was clumped within the graph, because the relationship between sensor reading and yield varied due to location, although the general trend was similar. The use of GBAO sensors have not been a supported N recommendation tool in North Dakota.

The relationship between sensor reading and yield is different in the corn production system compared to tillering mortality problems and exponential growth of corn begins about V6 compared to wheat (Gitelson, 1996; Miyneni et al, 1997). Corn yield prediction is prelated to plant population, plant size, uptake of N at V6 (Binford et al., 1992b; Plenet, 1995; Plenet and Lemaire, 1999). Therefore, yield can be estimated at V6 growth stage although some of the components of corn yield may already be established by V6 (Madonni and Otegui, 2003). Fertilized kernel number per ear is related with growth of corn at silking stage ± 10 days (Hall et al., 1981; Andrade et al., 1999). Sensor readings obtained during silking are difficult because of saturation in the red spectra (Andrade et al, 1996; Echarte et al, 2000). Vega and Sadras reported in 2003 that corn growth rate is positively and linearly related to the crop biomass during the critical periods of growth. Echarte and Andrade (2003) stated that the harvest index was found similar for the corn varieties released between the times of 1965 to 1993. This indicates that estimation of yield and potential for N response in relative terms is possible.

2.13. Corn Nitrogen Recommendation

The current North Dakota State University N recommendation for corn considers several components. These components include yield goal or expected yield, soil profile nitrate-N to 60-cm depth, and any anticipated N release due to the previous crop. The recommendation formula is

N rate = (Yield Potential) less soil nitrate to 60 cm less previous crop credit (Eq. 3)

There are numerous problems with this approach. This approach requires the grower to predict yield, which is nearly impossible from year to year. In recent studies in North Dakota, It predicts a linear N response under eastern high clay conventional-till sites, which is contrary to numerous N rate studies on corn on other crops, where the typical response is quadratic in form. The model also ignores any economic factors (price of corn for yield delivered and the cost of the N). The N rate calculation formula is relevant for all soils in all regions of the state and for all tillage systems. It also assumes that preplant N application is the accepted standard for all soils in the state, and that the formula will predict well in all rainfall environments.

There is ample evidence that eastern high clay conventional-till sites and eastern medium-textured coventional-till sites may experience serious N losses due to denitrification and/or leaching. If farmers decide to improve NUE through split N application, the use of GBAO's may aid in improving the N rate decision at the time of side-dress.

2.14. Objectives

The overall objective of the study was to develop farmer friendly technologies for on-the-go N management in dryland corn production under different soil and cultivation practices. In the dissertation, particular objectives were organized into separate chapters.

2.14.1. Chapter IV

Evaluate the crop height to improve relationship between the sensor readings and corn yield. The study was to explore the combination of corn plant height at two growth stages with two GBAO sensors, GS and CC, readings to develop a strong relationship between sensor readings and corn yield relationship. The objective was to use corn height to improve the relationship between active optical sensor readings and yield estimates.

2.14.2. Chapter V

Compare the two ground-based active-optical sensors, GS and CC for in-season estimation of corn yield. Different wavelengths are emitted and received by the two sensors that may result in different sensor reading results. The objective of study was to compare two ground-based active-optical sensors for in-season estimation of corn yield.

2.14.3. Chapter VI

Calibrate GS and CC senors for inseason N estimation under dryland cultivation with different soil textures as well as cultivation practices. The objective of the study was to build algorithms for use in directing in-season N rates for corn.

2.14.4. Chapter VII

Explore the possibilities of using GBAO sensors to detect sulfur deficiencies in corn. Two ground-based active-optical sensors, GS and CC were used with different wavelengths. The objective the study was to test the best wavelength for detecting sulfur deficiency and also compare the two GBAO sensors.

2.15. Literature Cited

Al-Abbas, A.H., R. Barr, J.D. Hall, F.L. Crane, and M.F. Baumagardner. 1974. Spectra of normal and nutrient-deficient maize leaves. Agron. J. 66:16-20.

Al-Khatib, K. and M.G. Paulsen. 1990. Photosynthesis and productivity during high temperature stress of wheat genotypes from major world regions. Crop Sci. 30:1127-1132.

Aldrich, S.R. and E.R. Leng. 1974. Producción moderna de maíz. Editorial Hemisferio Sur. Buenos Aires. Argentina. 307pp.

Andrade, F., A.G. Cirilo, S.A. Uhart, and M.E. Otegui. 1996. Ecofisiologia del cultivo de maiz. Editorial La Barrosa y Dekalb Press. 292 pp.

Andrade, F.H., C. Vega, S. Uhart, A. Cirilo, M. Cantarero, and O. Valentinuz. 1999. Kernel number determination in maize. Crop Sci. 39:453-459.

Anten, N.P.R., F. Schieving, E. Medina, M.J.A. Werger, and P. Schufflen. 1995. Optimal leaf area indices in C3 and C4 mono- and dicotyledonous species at low and high nitrogen availability. Int. J. Plant Bio. 95: 541-550.

Araus, J.L. 1996. Integrated physiological criteria associated with yield potential. p. 150-166. In M.P. Reynolds, S. Rajaram, and A. McNab (eds) Increasing yield potential in wheat: Breaking the barriers. Mexico, D.F.: CIMMYT.

Bandel, V.A., S. Dzienia, and G. Stanford. 1980. Comparison of N fertilizers for no-till sites corn. Agron. J. 72:337-341.

Bausch, W.C., and H.R. Duke. 1996. Remote sensing of plant nitrogen status in corn. T. Am. Soc. Agric. Eng. 39:1869-1875.

Belay, A., A.S. Claassens, and F.C. Wehner. 2002. Effect of direct nitrogen and potassium and residual phosphorous fertilizers on soil chemical properties, microbial components and corn yield under long-term crop rotation. Biol. Fertil. Soils. 35:420-427.

Binder, D.L., D.H. Sander, and D.T. Walters. 2000. Maize response to time of nitrogen application as affected by level of nitrogen deficiency. Agron. J. 92:1228-1236.

Binford, G.D., A.M. Blackmer, and M.E. Cerrato. 1992a. Relationships between corn yields and soil nitrate in late spring. Agron. J. 84:53-59.

Binford, G.D., A.M. Blackmer, and M.E. Cerrato. 1992b.Nitrogen concentration of young corn plants as an indicator of N availability. Agron. J. 84:219-223.

Blackmer, T.M., and J.S. Schepers. 1996. Aerial photography to detect Nitrogen Stress in Corn. J. Plant Physiol. 148, 440-444.

Blackmer, T.M., J.S. Schepers, G.E. Varvel, and E.A. Walter-Shea. 1996a. Nitrogen deficiency detection using reflected shortwave radiation from irrigated corn canopies. Agron. J. 88:1-5.

Blackmer, T.M., J.S. Schepers, G.E. Varvel, and G.E. Meyer. 1996b. Analysis of aerial photography for nitrogen stress within corn fields. Agron. J. 88:729-733.

Blackmer, T.M., J.S. Schepers, and G.E. Varvel. 1994. Light reflectance compared with other nitrogen stress measurements in corn leaves. Agron. J. 86:934-938.

Blackmer, T.M., and J.S. Schepers. 1994. Techniques for monitoring crop nitrogen status in corn. Comm. Soil Sci. Plant Anal. 25:1791-1800.

Blackmer, T.M., J.S. Schepers, and M.F. Vigil. 1993. Chlorophyll meter readings in corn as affected by plant spacing. Comm. Soil Sci. Plant Anal. 24:2507-2516.

Bock, B.R. 1984. Efficient use of nitrogen in cropping systems. p. 273-294. *In* R.D. Hauck (ed.) Nitrogen in crop production. ASA, CSSA, and SSSA, Madison, WI.

Bondada, B.R., D.M. Oosterhuis, R.J. Norman, and W.H. Baker. 1996. Canopy photosynthesis, growth, yield, and boll N accumulation under nitrogen stress in cotton. Crop Sci. 36:127-133.

Boyer, J.S. 1970. Differing sensitivity of photosynthesis to low leaf water potentials in corn and soybean. Plant. Physiol. 46:236-239.

Boyer, J.S. 1982. Plant productivity and the environment. Science. 218:443-448.

Bullock, D.G., and D.S. Anderson. 1998. Evaluation of the Minolta SPAD-502 chlorophyll meter for nitrogen management in corn. J. Plant Nutr. 21:741-755.

Bundy, L.G. 2000. Nitrogen recommendations and optimum nitrogen rates: How do they compare? p. 5–13. *In* Proc. North Central Ext.-Industry Soil Fertil. Conf., St. Louis, MO. Vol. 16. Potash and Phosphate Inst., Brookings, SD.

Camp, P.J., Huber S.C., Burke J J., Moreland D.E. 1982. Biochemical changes that occur during senescence of wheat leaves: I. basis for the reduction of photosynthesis. Plant Physiol. 70:1641-1646.

Carter, G.A. 1993. Responses of leaf spectral reflectance to plant stress. Am. J. Bot. 80:239-243.

Carter, G.A., and A.K. Knapp. 2001. Leaf optical properties in higher plants: linking spectral characteristics to stress and chlorophyll concentration. Am. J. Bot.. 88:677- 684.

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

CAST. 1999. Gulf of Mexico hypoxia: Land and sea interactions. Task Force Report No. 134. Council for Agricultural Science and Technology, Ames, IA.

Chen, J.M. and J. Cihlar. 1995. Retrieving leaf area index of boreal conifer forests using Landsat TM images. Remote Sens. Environ. 55: 153-162.

Chappelle, E.W., M.S. Kim, and J.E. McMurtrey III. 1992. Ratio analysis of reflectance spectra (RARS): an algorithm for the remote estimation of the concentrations of Chlorophyll A, Chlorophyll B, and Carotenoids in soybean leaves. Remote Sens. Environ. 39:239-247.

Ciganda, V., A.A. Gitelson, and J.S. Schepers. 2009. Non-destructive determination of corn leaf canopy chlorophyll content. J. Plant Physiol. 166:157-167.

Clay, D.E., K.I. Kim, J. Chang, S.A. Clay, and K. Dalsted. 2006. Characterizing water and nitrogen stress in corn using remote sensing. Agron. J. 98:579-587.

Colnenne, C., J.M. Meynard, R. Reau, E. Justes, and A. Merrien. 1998. Determination of a critical nitrogen dilution curve for winter oilseed rape. Ann. Bot. (London) 81:311–317.

Cowling, S.A. and C.B. Field. 2003. Environmental control of leaf area production: Implications for vegetation and land-surface modeling. Global Biogeochem. Cy. 17:1007.

Crafts-Brandner, S.J., and M.E. Salvucci. 2002. Sensitivity of photosynthesis in a C4 plant, corn, to heat stress. Plant Physiol. 129:1773-1780.

Crippen, R.E. 1990. Calculating the vegetation Index Faster. Remote Sens. Environ. 34:71-73.

Curran, P.J. 1983. Multispectral remote sensing for the estimation of green leaf area index. Philos. T. Roy. Soc. London. 309: 257-270.

Daughtry, C.S.T., C.L. Walthall, M.S. Kim, E.B. de Colstoun, and J.E. McMurtrey. 2000. Estimating corn leaf chlorophyll concentration from leaf and canopy reflectance. Remote Sens. Environ. 74:229-239.

Deering, D.W. 1978 Rangeland reflectance characteristics measured by aircraft and spacecraft sensors. Ph.D. dissertation. College Station.

Deering, D.W., J.W. Rouse Jr., R.H. Haas, and J.A. Schell. 1975. Measuring forage production of grazing units from LANDSAT MSS data. Proceedings of the 10th International Symposium on Remote Sensing of Environment.

Dellinger, A.E., J.P. Schmidt, and D.B. Beegle. 2008. Developing Nitrogen Fertilizer Recommendations for Corn Using an Active Sensor. Agronomy Journal 100:1546-1552.

Denmead O.T., and R.H. Shaw. 1960. The effects of soil moisture stress at different stages of growth on the development and yield of Corn. Agron. J. 52:272-274.

Dobermann, A., J.L. Ping, V.I. Adamchuk, G.C. Simbahan, and R. Ferguson. 2003. Classification of crop yield variability in irrigated production fields. Agron. J. 95: 1105-1120.

Dobermann, A., and K. G. Cassman. 2002. Plant nutrient management for enhanced productivity in intensive grain production systems of the United States and Asia. Plant Soil 247: 153-175.

Dwyer, L.M., D.W. Stewart, and M. Tellenaar. 1992. Analysis of corn leaf photosynthesis under drought stress. Can. J. Plant Sci. 72:477-481.

Echarte, L., S. Luque, F.H. Andrade, V.O. Sadras, A. Cirilo, M.E. Otegui, and C.R.C. Vega. 2000. Response of maize kernel number to plant density in Argentinean hybrids released between 1965 and 1995. Field Crops Res. 68:1–8.

Echarte, L., and F.H. Andrade. 2003. Harvest index stability of Argentinean maize hybrids released between 1965 and 1993. Field Crops Res. 82:1–12.

Eck, H.V. 1984. Irrigated corn yield response to nitrogen and water. Agron. J. 46:421-428.

Eghball, B. J.S. Schepers, M. Negahban, and M.R. Shaver. 2003. Spatial and temporal variability of soil nitrate and corn yield: multifractal analysis. Agron. J. 95:339-346.

Fageria, N.K., and V.C. Baligar. 2005. Enhancing nitrogen use efficiency in crop plants, Adv. in Agron. 88:97-185.

Fang, H., S. Liang, and A. Kuusk. 2003. Retrieving leaf area index using a genetic algorithm with a canopy radiative transfer model. Remote Sens. Environ. 85: 257-270.

Federer, C.A., and C.B. Tanner. 1966. Spectral distribution of light in the forest. Ecology. 47:55-560.

Ferguson, R.B., G.W. Hergert, J.S. Schepers, C.A. Gotway, J.E. Cahoon, and T.A. Peterson. 2002. Site-Specific nitrogen management of irrigated maize: yield and soil residual nitrate effects. Soil Sci. Soc. Am. J. 66:544-553

Ferguson, R.B., R.M. Lark, and G.P. Slater. 2003. Approaches to management zone definition for use of nitrification inhibitors. Soil Sci. Soc. Am. J. 67:937-947.

Filella, I., L. Serrano, J. Serra, and J. Penuelas. 1995. Evaluating wheat nitrogen status with canopy reflectance indices and discriminate analysis. Crop Sci. 35:1400-1405.

Flowers, M., R. Weisz, and J.G. White. 2005. Yield-based management zones and grid sampling strategies: Describing soil test and nutrient variability. Agron. J. 97:968-982.

Fox, R.H., J.M. Kern, and W.P. Piekielek. 1986. Nitrogen fertilizer source and method and time of application effects on no-till corn yields and N uptakes. Agron. J. 78:741-746.

Fox, R.H., and W.P. Piekielek. 1995. The relationship between corn grain yield goals and economic optimum nitrogen fertilizer rates. Agron. Ser. 136. Penn State Univ., University Park, PA.

Franzen, D.W., D.H. Hopkins, M.D. Sweeney, M.K. Ulmer, and A.D. Halvorson. 2002. Evaluation of soil survey scale for zone development of site-specific nitrogen management. Agron. J. 94:381-389.

Freeman, K.W., K. Girma, D.B. Arnall, R.W. Mullen, K.L. Martin, R.K. Teal, and W.R. Raun. 2007. By-plant prediction of corn forage biomass and nitrogen uptake at various growth stages using remote sensing and plant height. Agron. J. 99:530-536.

Fulton, J.M. 1970. Relationships among soil moisture stress, plant populations, row spacing and yield of corn. Can. J. Plant Sci. 50:31-38.

Gastal, F., and G. Lemaire. 2002. N uptake and distribution in crops: An agronomical and ecophysiological perspective. J. Exp. Bot. 53:789–799.

Gates, D.M., H.J. Keegan, J.C. Schleter, and V.R. Weidner. 1964. Spectral properties of plants. Appl. Optics. 4:11-20.

Gausman, H. W. 1974. Leaf reflectance of near-infrared, Photogramm. Eng. Remote Sens. 40:183-191.

Gausman, H. W. 1977. Reflectance of leaf components. Remote Sens. Environ. 6:1-9.

Gausman, H.W., and W.A. Allen. 1973. Optical parameters of leaves of 30 plant species. Plant Physiol. 52:57-62.

Gentry, L.E., and F.E. Below. 1993. Corn productivity as influence by form and availability of nitrogen. Crop Sci. 33:491-497.

Gilabert, M.A., S. Gandia, and J. Melia. 1996. Analyses of spectral biophysical relationships for a corn canopy. Remote Sens. Environ. 55:11-20.

Ginting, D., J.F. Moncrieg, and S.C. Gupta. 2003. Performance of a variable tillage system on interactions with landscape and soil. Precis. Agric. 4:19-34.

Gitelson, A.A., A. Viña, T.J. Arkebauer, D.C. Rundquist, G. Keydan, and B. Leavitt, 2003a. Remote estimation of leaf area index and green leaf biomass in maize canopies, Geophys. Res. Lett., 30:1248.

Gitelson, A.A., Y.J. Kaufman, and M.N. Merzlyak. 1996. Use of a green channel in remote sensing of global vegetation from EOS-MODIS. Remote Sens. Environ. 58:289-298.

Gitelson, A.A. 2004. Wide Dynamic Range Vegetation Index for Remote Quantification of Crop Biophysical Characteristics. J. Plant Physiol., Vol. 161, 165-173

Gitelson, A.A., U. Gritz, and M.N. Merzlyak. 2003b. Relationships between leaf chlorophyll content and spectral reflectance and algorithms for non-destructive. J. Plant Physiol. 160:271-282.

Gitelson, A.A., and M.N. Merzlyak. 1997. Remote estimation of chlorophyll content in higher plant leaves. Int. J. Remote Sens. 18:2691-2697.

Gitelson, A.A., A. Viña, D.C. Rundquist, V. Ciganda, and T.J. Arkebauer. 2005. Remote Estimation of Canopy Chlorophyll Content in Crops, Geophys. Res. Lett., 32.

Goos, R.J., and L. Prunty. 1990. Yield variability and the yield goal decision. p. 187-189. *In* J.L. Havlin (ed.) Proc. of the Great Plain Soil Fertility Conf., Denver, CO. 6-7 Mar. 1990. Kansas State Univ., Manhattan.

Govaers, B., N. Verhulst, K.D. Sayre, P. De Corte, B. Goudeseune, K. Lichter J. Crossa, J. Deckers, and L. Dendooven. 2007. Evaluating spatial within plot crop variability for Different management practices with an optical sensor. Plant Soil. 299:29-42.

Greenwood, D.J., G. Lemaire, G. Gosse, P. Cruz, A. Draycott, and J.J. Neeteson. 1990. Decline in percentage N of C3 and C4 crops with increasing plant mass. Ann Bot. 66: 425-436

Hall, A.J., J. H. Lemcoff, and N. Trapani. 1981. Water stress before and during flowering in maize and its effects on yield, its components, and their determinants. Maydica, 26:19-38.

Hansen, P.M. and J.K. Schjoerring. 2003. Reflectance measurement of canopy biomass and nitrogen status in wheat crops using normalized difference vegetation indices and partial least squares regression. Remote Sens. Environ. 86:542-553.

Harper, F. 1983. Principles of arable crop production. Granada Publishing, London 336pp.

Hatfield, J.L., A.A. Gitelson, and J.S. Schepers. 2008. Application of spectral remote sensing for agronomic decisions. Agron. J. Supplement. 100:117-131.

Hatfield, J.L. and J.H. Prueger. 2010. Value of using different vegetative indices to quantify agricultural crop characteristics at different growth stages under varying management practices. Remote Sens. 2:562-578.

Heiniger, R.W., R.G. McBride, and D.E. Clay. 2003. Using soil electrical conductivity to improve nutrient management. Agron. J. 95:508-519.

Henebry, G.M., K.M. de Beurs, and A.A. Gitelson. 2005. Land surface phenologies of Uzbekistan and Turkmenistan between 1982 and 1999. Arid Ecosys. 11:25-32.

Herrmann, A., and F. Taube. 2004. The range of the critical nitrogen dilution curve for maize (Zea mays L.) can be extended until silage maturity. Agron. J. 96:1131-1138.

Herrero, M.P., and R.R. Johnson. 1980. Drought stress and Its effects on corn reproductive systems. Crop Sci. 21:105-110.

Holland, K.H., and J.S. Schepers. 2010. Derivation of a Variable Rate Nitrogen Application Model for In-Season Fertilization of Corn. Agron. J. 102:1415-1424.

Huete, A.R. 1988. A soil-adjusted vegetative index (SAVI). Remote Sens. Environ. 25:295-309.

Hurley, T.M., G.L. Malzer, and B. Kilian. 2004. Estimating site-specific nitrogen crop response functions: A conceptual framework and geostatistical model. Agron. J. 96:1331-1343.

Inada, K. 1965. Studies for a method for determining the deepness of green color and chlorophyll content of intact crop leaves and its practical application. 2. Photoelectric characters of chlorophyll meter and correlation between the reading and chlorophyll content in leaves. Proc. Crop Sci. Soc. Japan, 33:301-308.

Inman, D., R. Khosla, R.M. Reich, and D.G. Westfall. 2007. Active remote sensing and grain yield in irrigated corn. Precis. Agric. 8:241-252.

Inman, D., R. Khosla, D.G. Westfall, and R. Reich. 2005. Nitrogen uptake across site specific management zones in irrigated corn production systems. Agron. J. 97:169-176.

Jacobs, B.C., and C.J. Pearson. 1991. Potential yield of corn determined by rates of growth and development of ears. Field Crops Res. 27:281-298.

Jaynes, D.B., and T.S. Colvin. 1997. Spatiotemporal variavility of corn and soybean yield. Agron. J. 89:30-37.

Jiang, P., and K.D. Thelen. 2004. Effects of soil and topographic properties on crop yield in a north-central corn-soybean cropping system. Agron. J. 96:252-258.

Johnson, C.K., D.A. Mortensen, B.J. Wienhold, J.F. Shanahan, and J.W. Doran. 2003. Site-specific management zones based on soil electrical conductivity in a semiarid cropping system. Agron. J. 95:303-315.

Jordan, C. F. 1969. Derivation of leaf area index from quality of light in the forest floor. Ecology 50: 663-666.

Justes, E., B. Mary, J.M. Meynard, J.M. Machet, and L. Thelier-Huché. 1994. Determination of a critical nitrogen dilution curve for winter wheat crops. Ann. Bot. (London) 74:397–407.

Kachanoski, R.G., I.P. O'Halloran, D. Aspinall, and P.Von Bertoldi. 1996. Delta yield: Mapping fertilizer nitrogen requirement for crops. Better Crops 80:20–23.

Keeney, D.R. 1982. Nitrogen management for maximum efficiency and minimum pollution ASA, CSSA, and SSSA, Madison, WI.

Kitchen, N.R., S.T. Drummond, E.D. Lund, K.A. Sudduth, and G.W. Buchleiter. 2003. Soil electrical conductivity and topography related to yield for three contrasting soil-crop systems. Agron. J. 95:483-495.

Kitchen, N.R., and K.W. Goulding. 2001. On-farm technologies and practices to improve nitrogen use efficiency. p. 335–369. *In* R.F. Follett and J.L. Hatfield (ed.) Nitrogen in the environment: Sources, problems, and management. Elsevier Science, Amsterdam, the Netherlands.

Kitchen, N.R., K.A. Sudduth, S.T. Drummond, P.C. Scharf, H.L. Palm, D.F. Roberts, and E.D. Vories. 2010. Ground-Based Canopy Reflectance Sensing for Variable-Rate Nitrogen Corn Fertilization. Agron. J. 102:71-84.

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

Knipling, E.B. 1970. Physical and physiological basis for the reflectance of visible and near ir radiation from vegetation. Remote Sens. Environ. 1:155-159.

Knyazikhin, Y., J. Glassy, J.L. Privette, Y. Tian, A. Lotsch, Y. Zhang, Y. Wang, J.T. Morisette, P. Votava, R.B. Myneni, R.R. Nemani, and S.W. Running. 1999. MODIS leaf area index (LAI) and fraction of photosynthetically active radiation absorbed by vegetation (FPAR) product (MOD15). Algorithm and theoretical basis document, NASA Goddard Space Flight Center, Greenbelt, MD 20771, U.S.A.

Koch, B., R. Khosla, W.M. Frasier, D.G. Westfall, and D. Inman. 2004. Economic feasibility of variable-rate nitrogen application utilizing site-specific management zones. Agron. J. 96:1572-1580.

Kogan, F., R. Stark, A. Gitelson, L. Jargalsaikhan, C. Dugrajav, and S. Tsooj. Derivation of pasture biomass in Mongolia from AVHRR-based vegetation health indices. Int. J. Remote Sens. 14:2889-2896.

Kravchenko, A.N., G.P. Robertson, K.D. Thelen, and R.R. Harwood. 2005. Management, topographical, and weather effects on spatial variability of crop grain yields. Agron. J. 97:514-523.

Kravchenko, A.N., D.G. Bullock, and H.F. Reetz. 2000. Correlation of corn and soybean grain yield with topography and soil properties. Agron. J. 92:75–83.

Ladha, J.K., H. Pathak, T.J. Krupnik, J. Six, and C. van Kessel. 2005. Efficiency of fertilizer nitrogen in cereal production: Retrospects and prospects. Adv. Agron. 87:85-156.

Lambert, D.M., J. Lowenberg-DeBoer, and G.L. Malzer. 2006. Economic analysis of spatial-temporal patterns in corn and soybean response to nitrogen and phosphorus. Agron. J. 98:43-54.

Lemaire, G., and J. Salette. 1984. Relation entre dynamique de croissance et dynamique de prélèvement d'azote pour un peuplement de graminées fouragères: I. Etude de l'effect du milieu. Agronomie (Paris) 4: 423:430

Lemaire, G., D. Plenet, and D. Grindley. 1997. Leaf N content as an indicator of crop N nutrition status. Pp.190-199. In G. Lemaire (ed) Diagnosis of the Nitrogen Status in Crops. Plant Growth Regul. 2:145-146.

Lory, J.A., Scharf, P.C., 2003. Yield goal versus delta yield for predicting fertilizer nitrogen need in corn. Agron. J. 95:994-999.

Lukina, E.V., K.W. Freeman, K.J. Wynn, W.E. Thomason, R.W. Mullen, A.R. Klatt, G.V. Johnson, R.L. Elliott, M.L. Stone, J.B. Solie, and W.R. Raun. 2001. Nitrogen fertilization optimization algorithm based on in-season estimates of yield and plant nitrogen uptake. J. Plant Nutr. 24:885–898.

Ma, B.L., M.J. Morrison, and L.M. Dwyer.1996. Canopy light reflectance and field greenness to assess nitrogen fertilization and yield of corn. Agron. J. 88:915-920.

Maddux, L.D., D.E. Kissel, and P.L. Barnes. 1984. Effects of nitrogen placement and application on irrigated corn. J. Fert. 1:86-89.

Madonni, G.A., and M.A. Otegui. 2004. Intra-specific competition in maize: early establishment of hierarchies among plants affects final kernel set. Field Crops Res. 85:1-13.

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

Martin, K.L., K. Girma, K.W. Freeman, R.K. Teal, B. Tubana, D.B. Arnall, B. Chung, O. Walsh, J.B. Solie, M.L. Stone, and W.R. Raun. 2007. Expression of variability in corn as influenced by growth stage using optical sensor measurements. Agron. J. 99:384-389.

Masoni, A., L. Ercoli, and M. Mariotti. 1996. Spectral properties of leaves deficient in iron, sulfur, magnesium, and manganese. Agron. J. 88:937-943.

Meghji, M.R., J.W. Dudley, R.J. Lambert, and G.F. Sprague. 1983. Inbreeding depression, inbred and hybrid grain yields, and other traits of maize genotypes representing three eras. Crop Sci. 24:545-549.

Meisinger, J.J. 1984. Evaluating plant-available nitrogen in soil-crop systems. p. 391–416. *In* R. D. Hauck et al. (ed.) Nitrogen in crop production. ASA-CSSA-SSSA, Madison, WI.

Meisinger, J.J., and G.W. Randall. 1991. Estimating nitrogen budgets for soil-crop systems. p 85-124. *In* R.F Follett *et al.* (ed.) Managing nitrogen for groundwater quality and farm profitability. SSSA. Madison, WI.

Meisinger, J.J., F.R. Magdoff, and J.S. Schepers. 1992. Predicting N fertilizer needs for corn in humid regions: Underlying principles. p. 7–27. *In* B.R. Bock and K.R. Kelley (ed.)

Predicting N fertilizer needs for corn in humid regions. Bull. Y-226. Tennessee Valley Authority, Muscle Shoals, AL.

Mengel, D.B., D.W. Nelson, and D.M. Huber. 1982. Placements of nitrogen fertilizers for no-till and conventional till corn. Agron. J. 74:515-518.

Miller, H.F., J. Kavanaugh, and G.W. Thomas. 1975. Time of N application and yields of corn in wet, alluvial soils. Agron. J. 67:401–404.

Mistele, B. and U. Schmidhalter. 2008. Estimating the nitrogen nutrition index using spectral canopy reflectance measurements. Eur. J. Agron. 29:184-190.

Moges, S.M., W.R. Raun, R.W. Mullen, K.W. Freeman, G.V. Johnson, and J.B. Solie. 2004. Evaluation of green, red, and near infrared bands for predicting winter wheat biomass, nitrogen uptake, and final grain yield. J. Plant Nutr. 27:1431-1441.

Moss, R.A., and W.E. Loomis. 1952. Absorption spectra of leaves. I. the visible spectrum. Plant Physiol. 27:370-391.

Mullen, R.W., K.W. Freeman, W.R. Raun, G.V. Johnson, M.L. Stone, and J.B. Solie. 2003. Identifying an in-season response index and the potential to increase wheat yield with nitrogen. Agron. J. 95:347-351.

Mulvaney, R.L., S.A. Khan, and T.R. Ellsworth. 2005. Need for a soil-based approach in managing nitrogen fertilizers for profitable corn production. Soil Sci. Soc. Am. J. 70:172–18.

Myneni, R. B., C.D. Keeling, C.J. Tucker, G. Asrar, and R.R. Nemani. 1997. Nature (London) 386:698-702.

Myneni, R.B., R.R. Nemani, and S.W. Running. 1997b. Estimation of global leaf area and absorbed PAR using radiative transfer models. IEEE Trans. Geosci. Remote Sens. 35:1380-1393.

Olson, R.A., W.R. Raun, Yang Shou Chun, and J. Skopp. 1986. Nitrogen management and interseeding effects on irrigated corn and sorghum and on soil strength. Agron. J. 78:856-862.

Osborne, S.L., J.S. Schepers, D.D. Francis, and M.R. Schlemmer. 2002. Use of spectral radiance to estimate In-Season biomass and grain yield in nitrogen and water stressed corn. Crop Sci. 42:165-171.

Plénet, D. 1995 Fonctionnement des cultures de maïs sous contrainte azotée. Détermination et application d'un indice de nutrition. PhD Thesis, Institut National Polytechnique de Lorraine, Université de Nancy-Metz, Nancy, France, 247 pp.

Plénet, D., and G. Lemaire. 1999. Relationships between dynamics of nitrogen uptake and dry matter accumulation in maize crops. Plant Soil. 216:65-82.

Pierce, F.J., and C.W. Rice. 1988. Crop rotation and its impact on efficiency of water and nitrogen use. p. 21-42. *In* W.L. Hargrove *et al.* (ed.) Cropping strategies for efficient use of water and nitrogen. ASA Special Publ. 51. ASA, CSSA, and SSSA, Madison, WI.

Raun, W.R., and G.V. Johnson. 1999. Improving Nitrogen Use efficiency for cereal production. Agron. J. 91:357-363.

Raun, W.R, J.B. Solie, G.V. Johnson, M.L. Stone, E.V. Lukina, W.E. Thomason, and J.S. Schepers. 2001. In-season prediction of potential grain yield in winter wheat using canopy reflectance. Agron. J. 93:131-138.

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, R.W. Mullen, K.W. Freeman, W.E. Thomason, and E.V. Lukina. 2002. Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. Agron. J. 94:815-351.

Reddy, G.B., and K.R. Reddy. 1993. Fate of nitrogen-15 enriched ammonium nitrate applied to corn. Soil Sci. Soc. Am. J. 57, 111–115.

Rice, C.W., and J.L. Havlin. 1994. Integrating mineralizable nitrogen indices into fertilizer nitrogen recommendations. p. 1-13. *In* J.L. Havlin *et al.* (ed.) Soil testing: Prospects for improving nutrient recommendations. SSSA Spec. Publ. 40. SSSA, Madison, WI.

Sala, O.E., R.B. Jackson, H. Mooney, and R.W. Howarth. 2000. Methods in Ecosystem Science, (Eds. O.E. Sala, R.B. Jackson, H.A. Mooney, and R.H. Howarth), Springer Verlag, New York, pp. 421.

Scharf, P.C. 2001. Soil and plant tests to predict optimum nitrogen rates for corn. J. Plant Nutr. 24:805-826.

Scharf, P.C., S.M. Brouder, and R.G. Hoeft. 2006. Chlorophyll meter readings can predict nitrogen need and yield response of corn in the north-central USA. Agron. J. 98:655-665.

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

Scharf, P.C., and J.A. Lory. 2002.Calibrating corn color from aerial photographs to predict sidedress nitrogen need. Agron. J. 94: 397-404.

Scharf, P.C., and J.A. Lory. 2009. Calibrating Reflectance Measurements to Predict Optimal Sidedress Nitrogen Rate for Corn. Agron. J. 101:615-625.

Scharf, P.C., S.M. Brouder, and R.G. Hoeft. 2006. Chlorophyll meter readings can predict nitrogen need and yield response of corn in the North-central USA. Agron. J. 98:655-665.

Schepers, A.R., J.F. Shanahan, M.A. Liebig, J.S. Schepers, S.H. Johnson, and A. Jr Luchiari. 2004. Appropriateness of management zones for characterizing spatial variability of soil properties and irrigated corn yields across years. Agron. J. 96:195-203.

Schepers, J.S., and A.R. Mosier. 1991. Accounting for nitrogen in nonequilibrium soil-crop systems. p. 125-138. *In* R.F. Follett *et al*. (eds.) Managing nitrogen for groundwater quality and farm profitability. SSA, Madison, WI.

Schepers, J.S., D.D. Francis, M. Vigil, and F.E. Below. 1992b. Comparison of corn leaf nitrogen concentration and chlorophyll meter readings. Commun. Soil Sci. Plan. 23:2173-2187.

Schepers, J.S., G.E. Varvel, and D.G. Watts. 1995. Nitrogen and water management strategies to reduce nitrate leaching under irrigated maize. J. Contam. Hydrol. 20:227-239.

Schepers, J.S., T.M. Blackmer, and D.D. Francis. 1992a. Predicting N fertilizer needs for corn in humid regions: using chlorophyll meters. p. 105-114. In B.R. Bock and K.R. Kelley (eds.) Predicting N Fertilizer Needs for Corn in Humid Regions. Bull. Y-226. National Fertilizer and Environmental Research Center, Muscle Shoals, AL.

Schepers, J.S., T.M. Blackmer, W.W. Wilhelm, and M. Resende, 1996. Transmitance and reflectance measurements of corn leaves from plants with different nitrogen and water supply. J. Plant Physiol. 148(5):523-529.

Schilling, K.E. 2002. Chemical transport from paired agricultural and restored prairie watersheds. J. Environ. Qual. 31:1184-1193.

Schlemmer, M.R., D.D. Francis, J.F. Shanahan, and J.S. Schepers. 2005. Remotely measuring chlorophyll content in corn leaves with differing nitrogen levels and relative water Content Agron. J. 97:106-112.

Schröder, J.J., J.J. Neeteson, O. Oenema, and P.C. Struik. 2000. Does the crop or the soil indicate how to save nitrogen in maize production? Reviewing the state of the art. Field Crops Res. 66, 277-278.

Shahandeh, H., A.L. Wright, F.M. Hons, and R.J. Lascano. 2005. Spatial and temporal variation of soil nitrogen parameters related to soil texture and corn yield. Agron. J. 97:772-782.

Shanahan, J.F., K. Holland, J.S. Schepers, D.D. Francis, M.R. Schlemmer, and R. Caldwell. 2003. Use of crop reflectance sensors to assess corn leaf chlorophyll content. p. 129-144. *In* (ed. T. VanToai, D. Major, M. McDonald, J. Schepers, and L. Tarpley) Digital Imaging and Spectral Techniques: Appl. Precis. Agric. Crop Phys. Special Pub. 66. ASA, Madison, WI. 2003.

Shanahan, J.F., N.R. Kitchen, W.R. Raun, and J.S. Schepers. 2008. Responsive in-season nitrogen management for cereals. Comput. Electron. Agric. 61:51-62.

Shanahan, J.F., J.S. Schepers, D.D. Francis, G.E. Varvel, W.W. Wilhelm, J.M. Tringe, M.S. Schlemmer, and D.J. Major. 2001. Use of remote sensing imagery to estimate corn grain yield. Agron. J. 93:583-589.

Shapiro, C.A. 1999. Using a chlorophyll meter to manage nitrogen applications to corn with high nitrate irrigation water. Commun. Soil Sci. Plan. 30:1037-1049.

Sharma, R.C. 1995. Tiller mortality and its relationship to grain yield in spring wheat. Field Crops Res. 6:55-60.

Shaver, T.M., R. Khosla, and D.G. Westfal. 2010. Evaluation of two ground-based active crop canopy sensors in corn: growth stage, row spacing, and sensor movement speed. Soil Sci. Soc. Amer. J. 74:2101-2108.

Shaver, T.M., R. Khosla, and D.G. Westfall. 2011. Evaluation of two crop canopy sensors for nitrogen variability determination in irrigated corn. Precis. Agric. Online Publication.

Sheehy, J.E., M.J.A. Dionora, P.L. Mitchell, S. Peng, K.G. Cassman, G. Lemaire, and R.L. Williams. 1998. Critical nitrogen concentrations: Implications for high-yielding rice (*Oryza sativa* L.) cultivars in the tropics. Field Crops Res. 59:31–41.

Sinclair, T.R., and T. Horie, T., 1989. Leaf nitrogen, photosynthesis, and crop radiation use efficiency: a review. Crop Sci. 29:90-98.

Slaton, M.R., E.R. Hunt, and W.K.Smith. 2001. Estimating near-infrared leaf reflectance from leaf structural characteristics. Am. J. Bot. 88:278-284.

Solari, F., J. Shanahan, R.B. Ferguson, J.S. Schepers, and A.A. Gitelson. 2008. Active sensor reflectance measurements of corn nitrogen status and yield potential. Agron. J. 100:571-579.

Sripada, R.P., R.W. Heiniger, J.G. White, and R. Weisz. 2005. Aerial color infrared photography for determining late-season nitrogen requirements in corn. Agron. J. 97:1443-1451.

Stanford, G., and J.O. Legg. 1984. Nitrogen and yield potential. p. 263-272. *In* R.D. Hauck (ed.) Nitrogen in crop production. ASA, CSSA, and SSSA, Madison, WI.

Steinheimer, T.R., K.D. Scoggin, and L.A. Kramer. 1998. Agricultural chemical movement through a field size watershed in Iowa: Surface hydrology and nitrate losses in discharge. Environ. Sci. Technol. 32:1048-1052.

Stone, M.L., J.B. Solie, W.R.Raun, R.W. Whitney, S.L. Taylor, and J.D. Ringer. 1996. Use of spectral radiance for correcting in season fertilizer nitrogen deficiencies in winter wheat. T. Am. Soc. Agric. Eng. 39:1623-1631.

Timlin, D.J., Y. Pachepsky, V.A. Snyder, and R.B. Bryant. 1998. Spatial and temporal variability of corn grain yield on a hillslope. Soil Sci. Soc. Am. J. 62:764-773.

Tollenaar, M. 1989. Genetic improvement in grain yield of commercial maize hybrids grown in Ontario from 1959 to 1988. Crop Sci. 29:1365-1371.

Tucker, C.J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sens. Environ. 8:127-150.

Ulrich, A. 1952. Physiological bases for assessing the nutritional requirements of plants. Ann. Rev. Plant Physiol. 3; 207-228.

USDA-NASS. 2003. http://www.ers.usda.gov/Data/FertilizerUse/ http://www.nass.usda.gov/census/census02/volume1/ne/st31_1_033_033.pdf

Van Oosterom, E.J., P.S. Carberry, and R.C. Muchow. 2001. Critical and minimum N contents for development and growth of grain sorghum. Field Crops Res. 70:55–73.

Vanotti, M.B., and L.G. Bundy. 1994. Corn nitrogen recommendations based on yield response data. J. Prod. Agric. 7:249-256. United States Department of Agriculture-National Agricultural Statistics Service. 2003. Stat. Fert. Pestic. Online.

Varvel, G.E., J.S. Schepers, and D.D. Francis. 1997. Ability for in-season correction of nitrogen deficiency in corn using chlorophyll meters. Soil Sci. Soc. Am. J. 59:1233-1239.

Vega, C.R.C., and V.O. Sadras. 2003. Size-dependent growth and the development of inequality in maize, sunflower and soybean. Ann. Bot. 91: 795-805.

Verhulst, N., B. Govaerts, K.D. Sayre, J. Deckers, I.M. Francois, and L. Dendooven. 2008. Using NDVI and soil quality analysis to assess influence of agronomic management on within plot spatial variability and factors limiting production. Plant Soil. 317:41-59.

Weiss, M., and F. Baret. 1999. Evaluation of canopy biophysical variable retrieval performances form the accumulation of large swath satellite data. Remote Sens. Environ. 70: 293-306.

Welch, L.F., D.L. Mulvaney, M.G. Oldham, L.V. Boone, and J.W. Pendleton. 1971. Corn yields with fall, spring, and sidedress nitrogen applications. Agron. J. 63:119–123.

Whittaker, R. H., and P. L. Marks. 1975. Methods of assessing terrestrial productivity. In: H. Lieth and R. H. Whittaker (Eds.). Primary productivity of the biosphere. Ecological Studies 14. Springer-Verlag. Pp.55-118.

Wibawa, W.D., D.L. Dludlu, L.J. Swenson, D.G. Hopkins, and W.C. Dahnke. 1993. Variable fertilizer application based on yield goal, soil fertility, and soil map unit. J. Prod. Agric. 6:255–261.

Wiegand, C.L., A.J. Richardson, and E.T. Kanemasu. 1979. Leaf area index estimates for wheat from Landsat and their implications for evapotranspiration and crop modeling. Agron. J. 71: 336-342.

Wolfe, D.W, D.W. Henderson, T.C. Hsiao, and A. Alvino. 1988. Interactive water and nitrogen effects on senescence of maize. II. Photosynthetic decline and longevity of individual leaves. Agron. J. 80:865-870.

Zhao, D., K.R. Reddy, V.G. Kakani, J.J. Read, and G.A. Carter. 2003. Corn (Zea mays L.) growth, leaf pigment concentrations, photosynthesis, and leaf hyperspectral reflectance properties as affected by nitrogen supply. Plant Soil. 257:205-217.

CHAPTER III. METHODS

3.1. Locations

Nitrogen rate trials with field corn were conducted on 48 sites in North Dakota in 2011, 2012, and 2013 (Table 1). The sites were established within larger farm fields with permission from farmer cooperators. The cooperators were a mix of farmers with whom NDSU researchers had worked with before, farmers recommended by county agents and farmers who volunteered after presentations about the project at winter meetings. Each experimental area did not receive supplemental N from the cooperator, but were planted by the cooperator using a corn hybrid of their choice and received herbicide applications at their discretion along with the rest of the field. The experimental design at each site was a randomized complete block with four replications and six treatments; check (no added N), 45, 90, 134, 179, and 224 kg N ha^{-1}, applied as ammonium nitrate by hand preplant within a week of planting. Each experimental unit (plot) was 6.1-m in length and 3.05-m in width. Locations were categorized into eastern high clay (soil survey description) conventional-till sites and eastern medium-textured conventional-till sites (soil survey description) soil types as well as long-term eastern no-till sites and west-river sites (generally no-till) cultivation by using multiple regression analysis. Soil suvey data was used to deffertiate eastern high clay conventional-till sites from eastern medium-textured coventional-till sites. Eastern high clay conventional-till sites had silty clay loam textures or higher clay while eastern medium-textured coventional-till sites included fine sandy loams, silt loam, loam, and sandy loam textures. Long-term eastern no-till sites were defined as sites in continuous no-till sites for at least six years.

3.2. Soil Sampling

Five soil sample cores were obtained from each site prior to field work using a 2.5-cm diameter hand probe to a depth of 0- 15 cm for phosphorous (P), potassium (K), zinc (Zn), pH, and organic matter and 0-60 cm in depth for residual nitrate. Fertilizer P and K were not applied by the cooperator if the nutrients were mixed with their preplant N requirement. Instead, the researchers applied P as mono ammonium phosphate and K as potassium chloride at rates consistent with soil analysis based recommendations (Franzen, 2010). If the site was deficient in Zn, the researchers applied zinc sulfate (36% granules) at a rate of 11 kg ha^{-1} Zn per acre as a broadcast at the time of treatment application. If the site proved to be S deficient at V6, an application of gypsum at 22 kg ha^{-1} S (112 kg ha^{-1} gypsum) was applied as granules over the top of the corn. After obtaining soil samples, they were air-dried, ground to pass through a 2 mm screen, and thoroughly mixed before analysis for soil pH, available P, K, Zn, and organic matter. Soil pH was analyzed using a 1:1 soil: deionized H_2O solution method (Watson and Brown, 1998); P by the Olsen method (Olsen et al., 1954b), potassium using the 1-N ammonium acetate method (Thomas, 1982). The DTPA extraction method (Lindsay and Norvell, 1978) coupled with atomic absorption spectroscopy detection was used for determination of available Zn. Organic matter was measured using the loss following ignition method (Schulte and Hopkins, 1996). A description of the methods used for soil analysis follows.

3.3. Soil pH Measurement

Swedish scientist Sorensen coined the term pH in 1909 (Sorensen, 1909); however, Gillespie and Hurst were the first who calculated pH electrometrically by using platinum-palladium black hydrogen gas electrode (Gillespie and Hurst, 1918). Many improvements on the design of the electrode have been made since 1918. In 1930, the glass electrode was introduced, helping to measure pH rapidly and efficiently. The most effective method of recording a soil pH measurement is with a pH meter. There are pH measurements that can be conducted using dyes or strips, such as the field wet chemical method described by Linsley and Bauer (1929) for use by farmers, but they are cumbersome and some use environmentally and physiologically harmful chemicals.

Soil pH is an indication of the acidity or alkalinity of soil and is measured in pH units. The pH ranges from 0 to 14 with pH value of 7 defined as the neutral point. As the concentration of hydrogen ion activity in the soil solution increases, the soil pH decreases. Soil is increasingly more acidic from pH 7 to 0 the and from pH 7 to 14 the soil is increasingly more alkaline or basic.

The soil pH is used as an indicator of whether a soil may have toxic levels of aluminum and manganese. The availability of most essential plant nutrients is affected by pH. By knowing a soil's pH, we may help diagnose nutritional problems of agricultural crops and other plants. High pH may result in low micronutrient availability (Sandor et al., 1986c).

In the NDSU Soil Testing laboratory, where the samples for this project were analyzed, the pH meter was calibrated for a pH range between 4 and 7. Ten grams soil was placed in a 40 ml plastic cup and then ten mililiter of deionized water was added to the sample. Samples were stirred vigorously using a glass stirring rod for 5 seconds to mix the soil with water. The mixture was allowed to stand for 10 minutes. The pH was measured by first restirring the sample mixture for two seconds, then inserting the electrode into the slurry sample mixture.

3.4. Phosphorus Determination

In the North Central region of the United States, most laboratories use the Bray and Kurtz P-1 soil test analysis (Bray and Kurtz, 1945) for estimating crop available phosphorus (P). The Bray and Kurtz P-1 test is well correlated with acid and neutral soils. The Bray and Kurtz P-1 test is also useful in soils that contain less than two percent of dolomite or calcium carbonate (Bauer et al., 1996; Olson et al., 1954a; Smith et al., 1957). When higher amounts of carbonate are present in the soil P during extraction can precipitate, making the Bray and Kurtz P-1 test impractical. (Bauer et al., 1996; Smith et al., 1957). The sodium bicarbonate (Olsen) extraction for crop-available P performs well on calcareous soils as well as acidic soils (Olson et al., 1954a; Watanabe and Olsen, 1965); however, it is more difficult to maintain extracting solutions over time than the Bray P1 extraction, and has a smaller range of values from low to high relative P availability. Therefore, the Bray was used as a standard in many North Central USA states for many years. (Bauer et al., 1996; Olson et al., 1954a; Smith et al., 1957).

North Dakota and South Dakota, where many soils are calcareous, use the sodium bicarbonate (Olsen) method for P determination (Laverty, 1963). Each state using the Olsen P extraction method has developed their own correlation and calibration for different crops.

Equipment and reagents needed used in this project by the NDSU Soil Testing Laboratory included pipettes, Olsen extracting solution (0.5 M $NaHCO_3$, pH 8.5), filter papers, filtration racks, deionized water, shaker, filter funnels, cuvette, reagent B (ascorbic acid/Mo/Sb color forming reagent). Determination of available P in the Olsen extractants was made using a colorimeter.

3.4.1. Procedure for olsen method of P determination

One g soil was scooped into a 50 ml Erlenmeyer flask using a standard 1-g soil scoop. To each flask, 20 mL of Olsen extracting solution (0.5-M NaHCO3, pH 8.5) was added and then the flasks were shaken at 200 cycles per minute for 30 minutes at room temperature that varied from 24 and 27°C. Each extract was filtered through Whatman No. 2 filter paper into a 25 ml glass filter tube. The extract was refiltered if the extract was found unclear. A 5 mL aliquot was transferred to a 50 ml container. Fifteen milliliter of deionized water was added to the flask and 5 ml of reagent

B color development agent was added. The mixture was allowed to stand for 10 minutes for color development. The solution was transferred into a cuvette, which was placed into the colorimeter with absorbance measured at 882 nm wavelength. The P standard curve was prepared by pipetting a 5 mL aliquot of each of the working standards, developing color, and reading intensity in the same manner as with the soil extracts. Intensity was plotted against concentration of the working standards. The concentration was determined in the soil extract from the measured intensity and standard curve.

Calculations for Olsen method: ppm P in soil = ppm P in filtrate x 20.

3.5. Nitrogen Analysis

The soil nitrate test before crop planting has been used extensively and successfully in the Great Plains region of the United States to estimate the crop nitrogen (N) requirement. Because of low rainfall in this region, as well as frozen soils to a rooting depth in winter following fall soil sampling in the northern Great Plains, the potential for nitrate loss through denitrification and leaching is minimal (Dahnke and Johnson, 1990; Hergert, 1987).

The pre-plant nitrate test is a measure of available N that can easily be obtained from soil testing. The results from a preplant nitrate test are usually subtracted, or a portion subtracted from the N recommendation equation. The pre-plant nitrate test is different from pre-sidedress nitrate test (PSNT) sometimes used in the central and eastern USA, which is more an index than a value to be subtracted from the N recommendation. The sampling for the pre-plant nitrate test can be done in the fall or before the crop planting in the spring. This approach provide more time for the soil sample analysis and execution of the decisions for N application as compared to PSNT. The N crediting and N recommendation decision procedure are given by Bundy and Sturgul (1994) and Schmitt and Randall (1994).

The procedure used to extract and analyze pre-plant nitrate is detailed by Bundy and Meisinger, 1994. Equipment and reagents used by the NDSU Soil Testing Laboratory to extract and determine residual nitrate are a scale, French square bottles, 2M KCl extracting solution, 50ml Erlenmeyer flasks, and a spectrophotometer.

3.5.1. Transnitralation of salicylic acid method for nitrate-N test

Ten gram soil from each sample was taken into a volumetric flask and then 20-ml water (extracting solution) was added into it. The flask was shaked for 30 minutes. After shaking 0.2 ml of aliquant was taken and mixed with 8/10 of ml H_2SO_4 and 5% salicylic acid. Whole mixer was stayed for 20 minutes and then 18ml of 1.7N NaOH was added depends upon the color of the sample. The color absorbtion was measured using a spectrophotometer (Model- Brinkmann PC-910 colorimeter) at 420nm wavelength.

3.6. K Test Procedure of Ammonium Acetate Extractable Method

One gram of soil was taken into the extraction flask (50-mL Erlenmeyer flask) and mixed with 20ml of ammonium acetate and shaked for 5 minutes. The mixer was filtered and then concentration was measured using an atomic absorption spectrophotometer (model- Buokmodel 210 VGL) on spectrometer mode.

3.7. Organic Matter Procedure of Loss of Weight on Ignition Method

Five gram of soil was placed into the crucible and placed in an oven for 2 hours for drying at 105°C. After weighting the dry soil, it was placed into a muffle furnace for 2 hours at 360°C. The soil was weighed again and this weight was subtracted from the initial oven-dry weight of the soil. Percent organic matter was calculated by the multiplying the difference between the two weights by 0.9375 (correction factor).

3.8. Zinc Procedure of DTPA Extractable Method

Ten grams of soil was placed into a 25-ml Erlenmeyer flask and mixed with 20-ml of 0.005-M DTPA solution. The flask was shaked for 2 hours and then filtered with Watman Number 2 filter paper. The concentration was read a on atomic absorption spectrophotometer (model-Buokmodel 210 VGL) using the absorption mode with a zinc lamp.

3.9. Ground Based Active-Optical Sensors (GBAO)

Crop reflectance is defined as the ratio of the amount of radiation reflected by an individual leaf or canopy to the amount of incident radiation. Green plants typically exhibit very low reflectance and transmittance in visible regions of the spectrum (400 – 700 nm) due to strong absorbance by photosynthetic and associated plant pigments (Chappelle et al., 1992). Chlorophyll responsible for photosynthesis absorbs light selectively. Leaves absorb mainly blue (~450 nm) and red (~660 nm) wavelengths and reflect mainly green (550 nm) wavelengths. Reflectance measurements at these wavelengths are indicators of leaf health and two-dimensional biomass. Reflectance and transmittance are usually high in the near-infrared (NIR) region of the spectrum (~700-1400 nm) because there is very little absorbance by subcellular organelles and pigments and also because there is considerable scattering at mesophyll cell wall interfaces (Gausman, 1974; Gausman, 1977; Slaton et al., 2001). Near-infrared light is more strongly absorbed by the soil than by the crop. Reflectance measurements at these wavelengths provide information on the vegetative biomass relative to exposed soil.

3.10. Sensor Descriptions

The GBAO sensors use diodes to generate modular light pulses in particular wavebands absorbed by plant tissues. The GS sensor measures incident and reflected light from plant at 660 ± 15nm (red) and 770 ± 15 nm (NIR). In the GS, light is emitted from diodes in alternate bursts such that the visible source pulses for 1 msec and then the NIR diode source pulses for 1 msec at 40,000 Hz. Each burst from a given source amounts to ~40 pulses before pausing for the other diode to emit its radiation (another 40 pulses). The illuminated area is ~60 by 1 cm, with the long dimension typically positioned perpendicular to the direction of travel. The field of view is approximately constant for heights between 60 and 120 cm above the canopy because of light collimation within the sensor. Outputs from the sensor are NDVI (green or red version) and simple ratio (visible/NIR).

The Holland Scientific CC sensor is a relatively easy to use instrument that currently comes with a five hour battery pack. The CC sensor (ACS-470, Holland Scientific) simultaneously emits three bands; two in the visible range (red 650nm, red-edge 730nm) and one in the NIR (760nm). The light source of the CC is a modulated polychromatic LED array. It can emit and measure the light spectrums in the range from 430 nm to 850 nm band width (BW). The sensor has a measurement filter range includes 450 nm (BW ±20 nm), 550 nm (BW ±20 nm), 650 nm (BW ±20 nm), 670 nm (BW ±11 nm), 730 nm (BW ±10 nm) and 760 nm (LWP) wavebands.

The sensor is calibrated using software developed by Holland Scientific, Lincoln, NE. Measurements can be collected at a rate of 2-20 readings per second, so each recorded value in a 20 foot length of plot is the average of about 4000 readings ,moving about 5 km hr^{-1}. Outputs of the sensor are bereflectance values that allow calculation of vegetation indices.

Green leaf reflectance is about 20 percent in the 500 to 700 nm range (green to red wavelength) whereas green leaf reflection in the red-edge range approaches 60 percent in the 700 to 750 nm range. The red spectrum measures plant biomass but it is sensitive to low chlorophyll content (3-5 $\mu g/cm^2$) (Gitelson and Merzlyak, 1997). The red-edge spectrum (700-750nm) is sensitive to a wide range of chlorophyll (0.3 – 45 $\mu g/cm^2$) (Gitelson and Merzlyak, 1997).

Therefore, the red wavelength will work during early growth stages whereas red-edge wavelength can be used during all vegetative growth stages especially late in the season when foliage masks the soil surface and the red wavelength NDVI values vary in a very narrow range; typically from 0.9 to 0.99. This is referred to as saturation.

The formula for NDVI and red-edge NDVI follows from Eq. 1:

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

$$Red\ Edge\ NDVI = \frac{NIR - Red\ Edge}{NIR + Red\ Edge}$$

Values of wavelengths we used for GS and CC sensor are defined below:

The GS emits two bands: visible and near infrared:

NDVI= (NIR – Red)/(NIR+Red)

(774nm reading – 656nm reading) / (774nm + 656nm)

CC-470 emits three bands: visible, red-edge, and near infrared:

NDVI= (NIR – Red) / (NIR+Red)

(760nm reading – 670nm reading) / (760nm + 670nm)

Or

NDVI= (NIR – Red-edge) / (NIR+Red-edge)

(760nm reading – 730nm reading) / (760nm + 730nm)

3.10.1. Sensing procedure

Both GS and CC_ ACS-470 (CC) readings were obtained when the corn was about V6 stage and again about 10 days to 2 weeks later when the corn reached the V12 stage. Readings were taken over the top of the corn whirl on the identical interior row of each plot where harvest was intended. All reflectance data, as appropriate, were inserted within the generalized NDVI expression:

$$(\text{NIR} - \text{Red or Red-edge})/(\text{NIR} + \text{Red or Red-edge})$$

The red-edge wavelength measurement differs from the red NDVI measurement because the red-edge measures plant chlorophyll content (Horler et al. 1983). The GS and CC readings consisted of a mean of between 30 and 50 individual readings from each plot. Means within a treatment were determined using in-house programs for GS and CC raw data developed for Excel (Franzen 2012). The relationship between sensor readings and yield was normalized using the value of the in-season estimate of yield (INSEY) (Raun et al. 2001). To calculate INSEY, the sensor reading is divided by the growing degree days from the date of planting. The INSEY reading is especially important when combining sites, as in this study, because it compensates for differences in sensor readings due to differences in growing degree day corn maturity. The value for sensor reading and corn height (INSEYH) was calculated using the sensor reading multiplied by the corn height in centimeters divided by growing degree days from planting.

3.11. Crop Height: Manual/SenixView

For manual height measurement, plant height was obtained from three representative plants in the row being sensed within each plot. A tape measure was used to measure corn height from the soil surface to about 5 cm above the corn whirl base with full open leaf. The height was measured at V6 and V12 growth stages of the crop on the same day as sensing was carried out. The three measurements were averaged to provide the corn height for each plot.

For automated height measurement, a height sensor base model Senixview TSPC-30S1-232 (Senix Corporation, Hinesburg, VT) was used during 2013. Height sensor was calibrated with the software provided along with the sensor. Sensor was mounted on a two-wheeler bicycle with front wheel smaller than rear wheel to maintain the uniform height and balance between the plot rows. Depending on the crop height, the height of the sensor from the ground was adjusted and measured from the soil surface each time before entering into the field. The values of sensor within the plot were subtracted from the value of the height of sensor from the ground. After collecting the data, negative or zero values were deleted from the file recorded on the computer. Dell Mini (Dell Lattitude 10ST2e), placed on the bicycle, was connected to the sensor to collect the height data. The software, SenixVIEW Version 3, was installed on the Dell Mini and then entered the software in logging mode while ready to record the data. Log rate was set at one sample per second. When entered in the experimental plot, record button was pressed on the Dell Mini screen (option in the software which prompt up on Dell Mini screen). When finished with data recording, stop button on the screen was pressed and data was saved Microsoft Excel with location name and time of sensing. The middle row of every plot was sensed. Because there was no external or internal device to stop the sensor collecting height data in-between the plots therefore, a person always moved with the sensor to cover it in between the plots and then the negative and zero values were deleted.

Fig. 1. Method of collecting data from SenixVIEW height sensor mounted on bicycle while connected with Dell Lattitude 10ST2e.

3.12. Plot Care- Hand Weeding, Timing of Lane Clearing

A 150-cm alleyway that had no fertilizer applied separated replications,. The alleys were allowed to grow corn until about V8 (8 laf stage of corn), and then the alleyways were cleared of corn using a hoe. Again, during sensing at V12 (12 leaf stage of corn) stage, surviving plants or weeds were removed in alleyways. Weeds were removed from the plots if found at V8, V12, and later growth stages. At the Leonard South site in 2013, significant volunteer corn made hoeing out the extra corn between and within rows essential for meaningful sensing. The volunteer corn was hoed at V5 and sensing conducted three days later at V6. Each experimental plot was was established within the main field outside of the end rows; the distance from the road varied depending on grower plans for end rows from about 30m to 60m from the road therefore a lane leading to the plots was hoed at the V8 stage to make sure that hand harvest could be conducted easily, with the burlap bags weighing from 5 to 20 kg each could more easily be carried from the field.

3.13. Harvest

An interior row (6.1-m in length) was hand harvested, dried to about 10 per cent moisture and then shelled using an Almaco® corn sheller in 2011. Moisture at shelling was determined on a grain subsample using a Dickey-John® moisture-test weight sensor (Dickey-John, Auburn, IL, USA). In 2012, a newer model Almaco® corn sheller was used that allowed complete shelling of wet corn, so corn was shelled directly out of the field without a need for drying. Moisture was measured on shelled grain using the same instrument as in 2011.

3.14. Statistical Analysis

Regression analyses was conducted on sensor readings and yield with yield as dependent variable, and INSEY or INSEYH were determined at V6 and V12 as the independent variable to evaluate the relationship between yield and INSEY multiplied with plant height at V6 and V12, respectively. The INSEY was defined as the sensor reading divided by the growing degree days from date of planting to date of sensor reading (Raun et al., 2001). INSEYH is a term further defined in these experiments as INSEY multiplied by crop height. A preliminary analysis in 2011 was conducted which compared the relationship of yield to INSEY and INSEYH using linear, quadratic, square root, logarithmic, and exponential. Following this preliminary analysis, exponential relationships were found to have a high frequency of describing the relationships compared to other models. Therefore, exponential models are presented throughout this thesis. Multiple regression analysis using the method of (http://www.ats.ucla.edu/stat/sas/faq/compreg2.htm) was used to determine whether the data should be segregated into long-term eastern no-till sites, eastern high clay conventional-till sites, and medium texture conventional sites. The analysis confirmed that segregation of the data into those categories improved the relationship between INSEY and yield overall.

The determination coefficient (r^2) value was used to evaluate the relationship of crop yield and sensor reading and crop yield with sensor reading multiplied with corn height at V6 and V12. The SAS procedure Proc Reg for Windows V9.2 (SAS Institute, Cary, NC) was used to calculate the r^2 and evaluate linear, quadratic, square root, and logarithmic regression models. SAS GLM was used to compare the N treatments. A P-value of 5% probability was used to differentiate the treatments from each other in terms of statistical differences between treatments.

3.15. Literature Cited

Bauer, A., E.B. Norum, J.C. Zubriski, and R.A. Young. 1966. Fertilizer for small grain production on summer-fallow in North Dakota. N. Dakota. Ag. Exp. Stn. Bull. No. 461.

Bray, R.H., and L.T. Kurtz. 1945. Determination of total, organic, and available form of phosphorus in soil. Soil Sci. 59:39-45.

Bundy, L.G., and J.J. Meisinger. 1994. Nitrogen availability indices. p. 951-984. *In* R.W. Weaver et al (ed.) Methods of Soil Analysis, Part 2, 3rd ed. Agron. Monogr. 9. ASA and SSSA, Madison, Wis.

Bundy, L.G., and S.J. Sturgul. 1994. Soil nitrate tests for Wisconsin cropping systems. Univ. of Wisconsin Ext. Pub. A3624.

Chappelle, E.W., M.S. Kim, and J.E. McMurtrey III. 1992. Ratio analysis of reflectance spectra (RARS): an algorithm for the remote estimation of the concentrations of Chlorophyll A, Chlorophyll B, and Carotenoids in soybean leaves. Remote Sens. Environ. 39:239-247.

Dahnke, W.C., and G.V. Johnson. 1990. Testing soils for available nitrogen. p. 127-139. *In* R.L. Westerman (ed.) Soil Testing and Plant Analysis, 3rd ed. SSSA, Madison, Wis.

Franzen, D. W. 2010. North Dakota fertilizer recommendation tables and equations. NDSU Extension Circular SF-882. North Dakota State University Extension Service, Fargo, ND.

Franzen, M. 2012. Program for initial analysis of GreenSeeker_ and Holland Crop Circle_ Sensor rawdata within Excel. Unpublished program. Fargo, ND.

Gausman, H.W. 1974. Leaf reflectance of near-infrared, Photogrammetric Eng. Remote Sens. 40:183-191.

Gausman, H.W. 1977. Reflectance of leaf components. Remote Sens. Environ. 6:1-9.

Gillespie, L.J., and L.A. Hurst. 1918. Hydrogen ion concentration-soil type-common potato scab. Soil Sci. 6:219-236.

Gitelson A.A., and M.N. Merzlyak. 1997. Remote estimation of chlorophyll content in higherplant leaves. J. Remote Sens. 18:2691-2697.

Hergert, G.W. 1987. Status of residual nitrate nitrogen soil tests in the United States. Soil Sci. Soc. Am. J. 21:73-88. *In* J.R. Brown (ed.) Soil testing: Sampling, correlation, calibration, and interpretation. ASA Special Publ. 21. ASA, CSSA, and SSSA, Madison, Wis.

Horler, D.N.H., M. Dockray, and J. Barber. 1983. The red-edge of plant leaf reflectance. Int. J. Remote Sens. 4:273-288.

Laverty, J.C. 1963. A modified procedure for determination of phosphorus in soil extracts. Soil Sci. Soc. Am. Proc. 27:360-361.

Lindsay, W.L., and W.A. Norvell. 1978. Development of a DTPA soil test for zinc, iron, manganese, and copper. Soil Sci. Soc. Am. J. 42:421–428.

Linsley, C.M., and F.C. Bauer. 1929. Test your soil for acidity. Circular 346. College of Agriculture and Agricultural Experiment Station, University of Illinois, Champaign, IL.

Olson, R.A., M.B. Rhodes, and A.F. Dreier. 1954a. Available phosphorus status in Nebraska soils in relation to series classification, time of sampling and method of measurement. Agron J. 46:175-180.

Olsen, S.R., C.V. Cole, F.S. Watanabe, and L.A. Dean.1954b. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circular 939. U.S. Government Printing Office, Washington, D.C.

Sandor, J.A., P.L. Gersber, and J.W. Hawley. 1986c. Soils at prehistoric terracing sites in New Mexico. III. Phosphorous, selected micronutrients, and pH. Soil Sci. Soc. Am. J. 50: 177–180.

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

Schulte, E.E., and B.G. Hopkins. 1996. Estimation of soil organic matter by weight-loss-on ignition. In F.R. Magdoff et al. (Eds.), Soil Organic Matter: Analysis and Interpretation (Chap. 3, pp. 21–31). SSSA Special Publication 46. Madison, WI: SSSA.

Slaton, M.R., E.R. Hunt, and W.K.Smith. 2001. Estimating near-infrared leaf reflectance from leaf structural characteristics. Amer. J. Bot. 88:278-284.

Smith, F.W., B.G. Ellis, and J. Grava. 1957. Use of acid fluoride solutions for the extraction of available phosphorus in calcareous soils and in soils to which rock phosphate has been added. Soil Sci. Soc. Am. Proc. 21:400-404.

Thomas, G.W. 1982. Exchangeable cations. In A. L. Page et al. (Eds.). Methods of soil analysis. Part 2. (Agronomy Monographs 9, pp. 159–165). Madison, WI: ASA and SSSA.

Watanabe, F.S., and S.R. Olsen. 1965. Test of an ascorbic acid method for determining phosphorus in water and NaHCO3 extracts from the soil. Soil Sci. Soc. Amer. Proc. 29, 677-78.

Watson, D., and J.R. Brown. 1998. pH and lime requirement. In Brown, J. R. (ed.) Recommended Chemical Soil Test Procedure for the North Central Region. North Central Regional Res. Pub. No. 221 (revised). Missouri Agric. Exp. Stat. SB 1001, Univ. of Missouri, Columbia, p. 13.

CHAPTER IV. USE OF CORN HEIGHT TO IMPROVE THE RELATIONSHIP BETWEEN ACTIVE OPTICAL SENSOR READINGS AND YIELD ESTIMATES

4.1. Abstract

Two GBAO sensors GS and CC were used within thirty established corn N-rate trials in North Dakota at the V6 and V12 growth stages in 2011 and 2012. Corn height was recorded manually at the date of sensor data collection. At the V6 growth stage, the GS relationship to yield and the INSEY (in-season estimate of yield = sensor reading/growing degree-days from planting) value was improved when the sensor reading was multiplied times corn height. At the V12 stage, using the GS, the INSEY relationship with yield was also generally increased when height was considered. The CC red NDVI INSEY relationship with yield was similar to the GS red NDVI INSEY. The CC red-edge NDVI INSEY relationship was increased with height only at the first sensor date, but not with the second. Segregating the thirty-site data set improved all INSEY relationships compared to pooling all sites.

Key Words: Canopy sensors, nitrogen, INSEY

4.2. Introduction

Corn is an important world crop used as livestock feed, human consumption and ethanol production. It is logical to develop fertilizer practices that can increase grower profitability as well as more efficient nitrogen (N) use. Nitrogen is the nutrient most universally limiting corn production. Nitrogen in soil comes from independent N-fixing organisms, organic matter mineralization, plant residue decomposition, and release of inorganic N from fixed soil sources. Since most soils do not release enough N to support high yields possible with modern plant genetics, supplemental N in the form of fertilizer N must often be applied. The N use efficiency of corn is generally low (Raun and Schepers 2008). One method of increasing N use efficiency may be in-season N deficiency detection and fertilization based on reflection of emitted light from active-optical sensors (Raun and Schepers 2008).

Ground-based active optical sensors (GBAO) have shown very promising results in predicting crop yield (Raun et al., 2001). Ground-based active-optical sensors based on red and near infrared (NIR) ratios or normalized differential vegetative index (NDVI, which is the formula (NIR – red) / (NIR + red)) measure leaf density of living vegetation and chlorophyll status of the crop before canopy closure. Sensor diodes generate modulated light (pulsed at~40,000 Hz) in wavebands that are absorbed by plant tissues in the case of chlorophyll and reflected in the case of biomass. Algorithms relating expected corn yield with both the GS and CC measurements obtained early in the growing season have been developed for a number of crops and regions. The GS algorithm developed for corn (Raun et al. 2005) relates corn yield measured in field experiments with 'in-season estimate of yield' or 'INSEY'. The INSEY number is derived from the GS measurements of NDVI, divided by growing degree days from the date of planting. The algorithm described by the regression relationship between corn yield and INSEY is then used to vary the rate of N to corn, using an estimate of the difference in corn yield predicted and the corn yield predicted from a N-rich strip within variety and field of interest, multiplied times the 1.25 % N in corn grain estimate divided by a N fertilizer application efficiency factor (values from >0 to 1).

The CC Sensor® algorithm for corn (Holland and Schepers 2010) calculates a ratio of vegetation index for the corn plants compared to reference plants that are deemed to have an adequate supply of N. This ratio is called the Sufficiency Index (SI) and is assumed to remain the same throughout the remainder of the growing season unless additional N fertilizer is applied. A good linear relationship exists between SI and yield estimates (Schepers and Holland 2013). An N-rich area can be used to establish a vegetation index value for the reference part of the field, but this is not required when using a virtual reference approach (Holland and Schepers 2014). In research studies, the high-N plot is frequently used to provide the reference vegetative index.

Plant height alone has also been used as a metric during the vegetative growth of corn. Corn plant height is influenced by the water content in the soil (Hussain et al. 1999), soil texture (Kladivko et al. 1986), rate of fertilizer application (Kapusta et al. 1996) and cultivation methods (Kladivko et al. 1986). Measurement of plant height can be conducted using high resolution ultra-sound distance sensing of the crop canopy (Shrestha et al. 2002; Katsvairo et al. 2003).

Sugar beet (*Beta vulgaris* L.) canopy height multiplied times a GS reading was used in Minnesota to better estimate leaf N concentration, sugar beet top N content and dry matter yield (Franzen et al. 2003). The NDVI measurement is related to leaf area index, which is a two dimensional representation of crop growth and development. The NDVI measurement is related to leaf area index best at early to medium growth stages in corn, but the relationship becomes increasingly poor later in corn growth due to saturation of readings (Wilhelm et al. 2000; Haboudane et al. 2004).

Since the N content of sugar beet tops is not only related to the two dimensional leaf area, but its density, multiplying NDVI times canopy height results in a 'leaf volume' instead of a leaf area index (Franzen et al. 2003). In experiments with other crop types with different leaf and growth architectures, NDVI measurements were related to plant height in alfalfa (*Medicago sativa* L.), where plant height and surface area coverage develop nearly simultaneously, but were not related to plant height in grasses, where surface coverage was nearly continuous (Payero et al. 2004).

In corn, surface coverage by leaves is nearly complete by V10 in 50-cm to 75-cm spaced row widths, but corn height can vary considerably at nearly all growth stages. Investigating the relationship of corn attributes with yield, Machado et al. (2002) found that about 60 % of yield variability could be explained using corn height. Freeman et al. (2007) and Martin et al. (2012) used corn height in addition to a GS sensor to help estimate by-plant yield. Both studies resulted in high correlation between yield and plant height multiplied by INSEY. Corn height itself has been related directly with yield estimates (Katsvairo et al. 2003; Machado et al. 2002; Yin et al. 2011a; Yin et al. 2011b). If crop height can predict corn yield accurately and efficiently, its use within an algorithm that includes a GBAO sensor reading may enable an improved method to direct in-season N rates required for different parts of a field. There has been considerable research to develop GBAO sensor-based fertilizer recommendations (Biermacher et al. 2006; Ortiz-Monasterio and Raun 2007; Raun et al. 2001; Teal et al. 2006; Tubana et al. 2008). The relationship with GBAO sensor readings and yield has been increased in by-plant corn studies by multiplying sensor readings by corn plant height (Freeman et al. 2007; Martin et al. 2012).

The objective of this study was to explore the combination of corn plant height at two growth stages with the GS sensor readings or the CC Sensor® ACS 470 readings in improvement of the GBAO sensor and corn yield relationship.

4.3. Material and Methods

Thirty sites in southeastern North Dakota were used to conduct N rate trials on field corn in 2011 and 2012 (Table 1). Six sites were located in Sargent County, eleven in Richland County and thirteen in Cass County. The sites were established within larger farm fields. The experimental area at each site did not receive supplemental N from the cooperator, but was planted by each cooperator and received herbicide applications at their discretion along with the rest of the field. Each field was planted with a corn hybrid chosen by the cooperator for the entire field. The experimental design at each site was a randomized complete block with four replications and six treatments; check (no added N), 45, 90, 135, 179 and 224 kg N ha^{-1}, applied as ammonium nitrate by hand preplant within a week of planting. Each experimental unit (plot) was 6.1-m in length and 3.05-m wide. A 150-cm alleyway that had no fertilizer applied separated replications from each other. The alleys were allowed to grow corn until about V8, and then the alleyways were cleared of corn using a hoe. Due to differences in farmer cooperator planter spacing, with row widths from 50-cm to 75-cm wide, there were between 4 and 6 rows represented within plots. An examination of the yield response of the sites to N suggested that eastern high clay conventional-till sites (those whose clay content was greater than 30 %) responded differently to N compared to lower clay sites. Similarly, sites that had been in a eastern no-till sites/one-pass seeding tillage system responded differently to N rate compared to conventionally tilled locations. A multiple regression analysis was conducted on the sites with categories of soil texture (eastern high clay conventional-till sites or eastern medium-textured coventional-till sites) and tillage (greater than six consecutive years in eastern no-till sites and conventional tillage). The results strongly indicated that yield responses to N in this data set were dissimilar for eastern high clay conventional-till sites and other soil textures and also for eastern no-till sites compared to conventionally tilled sites (data not shown). The locations were therefore categorized into eastern high clay conventional-till sites and eastern medium-textured coventional-till sites soil types as well as eastern no-till sites and conventional cultivation (Table 2). Analysis of sensor readings, corn height and corn yield were conducted using these location categories.

Eight soil sample cores were obtained from each site prior to field work using a 2.5-cm diameter hand probe to a depth of 0-15 cm for phosphorus (P), potassium (K), zinc (Zn), pH, and organic matter and 0-60 cm in depth for residual nitrate. After obtaining soil samples, they were air-dried, ground to pass through a 2-mm screen and thoroughly mixed before analysis for soil pH, available P, K, Zn and organic matter. Soil pH was measured in a 1:1 ratio of soil to deionized H_2O solution (Watson and Brown 1998) , P by the Olsen method (Olsen et al. 1954) and K was analyzed using the 1-N ammonium acetate method (Thomas 1982). The DTPA extraction method (Lindsay and Norvell 1978) and detection with atomic absorption spectroscopy was used for determination of for Zn and organic matter was measured using the loss following ignition method (Schulte and Hopkins 1996). Phosphorus, K and Zn not applied by the cooperator were applied according to Franzen (2010), directed by soil test results. Two handheld GBAO sensors were used in the study: GS and CC. The CC sensor emits modulated white light that is filtered to record three wavebands of reflected light. In the case of this study, red, red-edge and NIR filters were installed that corresponded to 670, 730 and 760 nm. The CC sensors were calibrated using hardware and software developed by Holland Scientific. Reflectance measurements were obtained at 10 Hz for these experiments. The height of the sensors above the canopy at the time of sensing was 75 cm, with a light footprint of the CC of 0.56 times the height, or 42 cm width. The light footprint width of the GS is 37 cm.

The GS emits 2 wavebands of light; 660 ± 15 nm (red) and 770 ± 15 nm (NIR). Light is emitted from diodes in alternate bursts: the red source pulses for 1 msec and NIR diode source pulses 1 msec at 40,000 Hz. Each burst from the diodes amounts to ~40 pulses before pausing for the other diode to emit its radiation (another 40 pulses). The illuminated area is approximately 60-cm by 1-cm, with the long dimension typically positioned perpendicular to the direction of sensor movement. The field of view is generally constant for sensor heights between 60 and 120 cm above the canopy. Output from the sensor is Normalized differential vegetative index. Variations in height within the previously stated canopy/instrument distance limits cancel-out as long as both reflectance bands are responding to changes within the plant canopy.

Both GS and CC readings were obtained when the corn was about V6 stage and again after 14-15 days, when the corn reached the V12 stage. Readings were taken over the top of the corn whirls on the identical interior row of each plot where harvest was intended. All reflectance data, as appropriate, were inserted within the generalized NDVI expression: (NIR – red or red-edge) / (NIR + red or red-edge). The red-edge wavelength measurement differs from the red NDVI measurement because the red- edge measures plant chlorophyll content (Horler et al. 1983). The GS and CC readings consisted of a mean of between 30-50 individual readings from each plot. Means within a treatment were determined using in-house programs for GS and CC raw data developed for Excel (Franzen 2012). The relationship between sensor readings and yield was normalized using the value of the in-season estimate of yield (INSEY) (Raun et al., 2001). To calculate INSEY, the sensor reading is divided by the growing degree days from the date of planting. The INSEY reading is especially important when combining sites, as in this study, because it compensates for differences in sensor readings due to differences in growing degree day corn maturity. Means for each N treatment sensor readings and yield were calculated using SAS 9.1 for windows. The value for sensor reading and corn height (INSEYH) was calculated using the sensor reading multiplied by the corn height in centimeters divided by growing degree days from planting.

Plant height was obtained in centimeters from three representatively selected plants in the row being sensed within each plot. A tape measure was used to measure corn height from the soil surface to about 5 centimeters above the corn whirl base. The height was measured at V6 and V12 leaf stage of the crop on the same day as sensing was carried out. The three measurements were averaged to provide the corn height for each plot.

Table 1. GPS coordinates and soil series for field experiments, 2011 and 2012.

Year	Locations	GPS coordinates	Soil Type†
2011	Valley City	46° 52' 49.090" N, 97° 54' 46.240" W	Fine-loamy, mixed, superactive, frigid Calcic Hapludolls
	Rutland	45° 59' 58.051" N, 97° 28' 43.634" W	Fine-loamy, mixed, superactive, frigid Pachic Argiudolls
	Havana	45° 56' 04.266" N, 97° 35' 54.633" W	Fine-silty, mixed, superactive, frigid Pachic Hapludolls
	Durbin	46° 51' 29.495" N, 97° 09' 26.907" W	Fine, smectitic, frigid Typic Epiaquerts
	Mooreton	46° 12' 40.420" N, 96° 46' 43.259" W	Fine, smectitic, frigid Typic Epiaquerts
	Great Bend	46° 07' 54.977" N, 96° 43' 11.481" W	Fine, smectitic, frigid Typic Natraquerts
	Fairmount	45° 59' 39.021" N, 96° 35' 46.219" W	Fine-loamy, mixed, superactive, frigid Aeric Calciaquolls
	Christine	46° 53' 30.423" N, 96° 54' 05.749" W	Fine, smectitic, frigid Typic Epiaquerts
	Prosper	46° 56' 55.978" N, 97° 02' 48.344" W	Fine, smectitic, frigid Typic Calciaquerts
	Milnor	46° 16' 34.108" N, 97° 28' 02.389" W	Sandy, mixed, frigid Oxyaquic Hapludolls
	Page 2	47° 09' 36.755" N, 97° 25' 48.088" W	Fine-loamy, mixed, superactive, frigid Calcic Hapludolls
	Buffalo	46° 56' 51.974" N, 97° 28' 01.950" W	Fine-loamy, mixed, superactive, frigid Calcic Hapludolls
	Page 1	47° 09' 05.282" N, 97° 23' 21.552" W	Coarse-loamy, mixed, superactive, frigid Pachic Hapludolls
	Walcott	46° 30' 02.183" N, 97° 02' 32.182" W	Coarse-loamy, mixed, superactive, frigid Aquic Pachic Hapludolls
	Arthur	47° 03' 43.560" N, 97° 08' 04.248" W	Coarse-silty, mixed, superactive, frigid Aeric Calciaquolls
2012	Rutland East	45° 59' 36.599" N, 97° 27' 28.969" W	Fine-loamy, mixed, superactive, frigid Pachic Argiudolls
	Rutland west	45° 59' 32.671" N, 97° 30' 15.115" W	Fine-silty, mixed, superactive, frigid Aeric Calciaquolls
	Leonard-North	46° 42' 04.081" N, 97° 16' 52.371" W	Fine-silty, mixed, superactive, frigid Aeric Calciaquolls
	Casselton North	46º56’ 12.417” N, 97º 17’ 00.351”W	Fine-silty, mixed, superactive, frigid Aeric Calciaquolls
	Amenia	47° 00' 13.913" N, 97° 12' 57.025" W	Coarse-silty, mixed, superactive, frigid Aeric Calciaquolls
	Casselton South	46° 56' 26.922" N, 97° 17' 00.351" W	Fine, smectitic, frigid Typic Epiaquerts
	Galchutt	46° 23' 00.519" N, 96° 43' 48.576" W	Fine, smectitic, frigid Typic Natraquerts
	Fairmount North	45° 59' 38.268" N, 96° 38' 18.155" W	Coarse-silty, mixed, superactive, frigid Aeric Calciaquolls
	Fairmount South	45° 57' 23.964" N, 96° 34' 35.244" W	Fine-loamy, mixed, superactive, frigid Aeric Calciaquolls
	Great Bend	46° 08' 20.469" N, 96° 44' 09.026" W	Fine, smectitic, frigid Typic Natraquerts
	Prosper	46° 58' 10.307" N, 96° 59' 20.466" W	Fine, smectitic, frigid Typic Epiaquerts
	Barney	46° 10' 58.074" N, 96° 55' 43.331" W	Fine, smectitic, frigid Typic Epiaquerts

(continues)

Table 1. GPS coordinates and soil series for field experiments, 2011 and 2012 (continued)

Year	Locations	GPS coordinates	Soil Type†
2012	Mooreton	46° 18' 13.407" N, 96° 51' 40.672" W	Coarse-loamy, mixed, superactive, frigid Aeric Calciaquolls
	Gardner	47° 09' 57.820" N, 97° 02' 59.152" W	Fine, smectitic, frigid Vertic Argialbolls
	Arthur	47° 06' 25.800" N, 97° 14' 36.562" W	Fine, smectitic, frigid Vertic Argialbolls
	Wheatland	46° 55' 06.854" N, 97° 23' 14.391" W	Fine-loamy, mixed, superactive, frigid Aeric Calciaquolls
	Milnor	46° 13' 11.317" N, 97° 25' 31.110" W	Fine-loamy, mixed, superactive, frigid Pachic Argiudolls
	Leonard South	46° 40' 32.061" N, 97° 17' 02.579" W	Sandy, mixed, frigid Typic Endoaquolls
	Walcott west	46° 30' 29.560" N, 97° 03' 00.760" W	Coarse-loamy, mixed, superactive, frigid Aeric Calciaquolls
	Walcott east	46° 29' 44.107" N, 96° 53' 04.456" W	Coarse-silty over clayey, mixed over smectitic, superactive, frigid Aeric Calciaquolls

† information collected from Soil Survey Staff, 2013

Table 2. Tillage system, planting date and date of the first and second sensing of each location, 2011 and 2012.

Year	Locations	Tillage/Soil Type	Planting Date	1st Sensing	2nd Sensing
2011	Valley City	Eastern no-till sites	05/10/11	06/24/11	07/14/11
	Rutland	Eastern no-till sites	05/19/11	06/30/11	07/14/11
	Havana	Eastern no-till sites	05/17/11	06/30/11	07/14/11
	Durbin	Eastern high clay conventional-till sites	05/08/11	06/20/11	07/13/11
	Mooreton	Eastern high clay conventional-till sites	05/17/11	07/01/11	07/13/11
	Great Bend	Eastern high clay conventional-till sites	05/13/11	06/20/11	07/13/11
	Fairmount	Eastern high clay conventional-till sites	06/04/11	07/12/11	07/26/11
	Christine	Eastern high clay conventional-till sites	05/19/11	07/01/11	07/19/11
	Prosper	Eastern high clay conventional-till sites	05/25/11	07/06/11	07/18/11
	Milnor	Eastern medium-textured conventional-till sites	05/16/11	06/30/11	07/14/11
	Page 2	Eastern medium-textured conventional-till sites	05/19/11	07/05/11	07/18/11
	Buffalo	Eastern medium-textured conventional-till sites	05/18/11	07/06/11	07/18/11
	Page 1	Eastern medium-textured conventional-till sites	05/19/11	07/05/11	07/18/11
	Walcott	Eastern medium-textured conventional-till sites	05/18/11	07/01/11	07/19/11
	Arthur	Eastern medium-textured conventional-till sites	05/17/11	07/05/11	07/18/11
2012	Rutland east	Eastern no-till sites	05/17/12	06/11/12	06/25/12
	Rutland west	Eastern no-till sites	05/01/12	06/11/12	06/25/12
	Leonard-North	Eastern high clay conventional-till sites	04/26/12	06/12/12	06/25/12
	Casselton North	Eastern high clay conventional-till sites	04/22/12	06/12/12	06/25/12
	Amenia	Eastern high clay conventional-till sites	04/09/12	06/04/12	06/25/12
	Casselton South	Eastern high clay conventional-till sites	04/22/12	06/12/12	06/25/12
	Galchutt	Eastern high clay conventional-till sites	05/09/12	06/13/12	06/26/12
	Fairmount West	Eastern high clay conventional-till sites	04/26/12	06/11/12	06/26/12
	Fairmount south	Eastern high clay conventional-till sites	05/09/12	06/11/12	06/26/12
	Great Bend	Eastern high clay conventional-till sites	05/11/12	06/13/12	06/26/12
	Prosper	Eastern high clay conventional-till sites	04/24/12	06/12/12	06/25/12

(continues)

Table 2. Tillage system, planting date and date of the first and second sensing of each location, 2011 and 2012 (continued)

Year	Locations	Tillage/Soil Type	Planting Date	1st Sensing	2nd Sensing
2012	Barney	Eastern high clay conventional-till sites	04/30/12	06/11/12	06/26/12
	Mooreton	Eastern medium-textured conventional-till sites	04/24/12	06/11/12	06/26/12
	Gardner	Eastern medium-textured conventional-till sites	04/25/12	06/12/12	06/25/12
	Arthur	Eastern medium-textured conventional-till sites	04/23/12	06/04/12	06/25/12
	Wheatland	Eastern medium-textured conventional-till sites	04/16/12	06/12/12	06/25/12
	Milnor	Eastern medium-textured conventional-till sites	04/15/12	06/13/12	06/25/12
	Leonard South	Eastern medium-textured conventional-till sites	04/09/12	06/12/12	06/25/12
	Walcott west	Eastern medium-textured conventional-till sites	04/30/12	06/11/12	06/25/12
	Walcott east	Eastern medium-textured conventional-till sites	04/26/12	06/13/12	06/25/12

The entire length of an interior row (6.1-m in length) was hand harvested. Although the alleyways between replications were not cleared of corn until V8, there was some alleyway effect as evidenced by larger ears in all plots in the plant next to the alleyway on each side. However, the sensor was used on all plants within the plot, so it was determined to harvest all plants within the plot for the relationship to be most valid. The ears were dried to about 10 per cent moisture and then shelled using an Almaco® corn sheller (Almaco, Nevada, IA, USA) in 2011. Moisture at shelling was determined on a grain subsample using a Dickey-John® moisture-test weight instrument (Dickey-John, Auburn, IL, USA). In 2012, a newer model Almaco corn sheller was used that allowed complete shelling of wet corn, so corn was shelled directly out of the field without a need for drying. Moisture was measured on shelled grain using the same instrument as in 2011.

Regression analyses were conducted on vegetation indices and yield with yield as the dependent variable. Both INSEY and INSEYH (INSEY multiplied times height) were determined at V6 and V12 as the independent variable to evaluate the relationship between yield and sensor readings. To assess the relationship, linear, quadratic, square root, logarithmic, and exponential models were considered. The exponential model proved to most consistently represent the relationships. Conceptually, relationships between measurements at different growth stages of corn before the reproductive stage would be represented best by an exponential model (Vanderlip and Fjell 1994). Regression analyses were conducted on data from eastern no-till sites, eastern medium-textured coventional-till sites and eastern high clay conventional-till sites.

The regression coefficient (r^2) value was used to evaluate the relationship of crop yield and sensor reading and crop yield with sensor reading multiplied with corn height at V6 (six leaf stage of corn) and V12 (12 leaf stage of corn) satge. The SAS procedure for Windows V9.2 (SAS

Institute, Cary, NC) was used to calculate the r^2 and evaluate the linear ($y = mx + b$), quadratic ($y= ax2+ bx + c$), and exponential ($y=ab^x$) regression models. To evaluate differences between regression coefficient values, a regression ANOVA procedure was utilized as described by UCLA-IDRE using SAS (IDRE-UCLA 2013). Comparisons were made using this procedure of regression coefficients between sensor readings with and without height considered, and between different sensor readings. Statements regarding whether regression coefficients are greater, less than, or similar to another are made with reference to these statistical procedures.

The formula for INSEY using either the GS or CC sensor:

INSEY = (sensor reading) / (growing degree days after planting)

The formula for INSEY using either the GS or CC with corn height considered (INSEYH):

INSEYH = ((sensor reading) x (corn height cm)) / (growing degree days after planting)

4.4. Results

The yield response curves describing the relationship of yield with applied N for all sites within each site category were generally quadratic (data not shown). Exceptions to this relationship were several eastern high clay conventional-till sites in 2011 where the response was linear. The quadratic relationship for most of the sites indicates that higher rates of N were not required. The linear relationship in the eastern high clay conventional-till sites in the wet year suggests that there was an opportunity to increase N use efficiency if N application followed early growing season wetness instead of preplant N application.

The *P* value and r^2 for the regression between INSEY and INSEYH for the regression where yield was modeled as a function of INSEY and INSEYH were found similar for linear, quadratic, logarithmic, and exponential regression models under each cropping system and soil textures in both the experimental year and combined data years at V6 and V12 growth stages, as well as sensor type (data not shown). The exponential regression model tended to most consistently represent relationships. Previous work by Raun et al. (2005) typically used exponential regression relationships. Growth of corn up to the reproductive stage also fits an exponential model (Vanderlip and Fjell 1994). Therefore, the exponential model was used to compare relationships in Tables 3 through Table 6.

The relationship between height alone and yield was examined for all site categories, eastern no-till sites, eastern high clay conventional-till sites, and eastern medium-textured coventional-till sites over both years. The only significant relationship of height alone with yield was in eastern medium-textured coventional-till sites in 2011 (r^2 = 0.41). The combination of height and sensor reading was more important in improving yield prediction.

The INSEY and corn yield relationship for eastern medium-textured conventional-till sites conventional till sites was improved at the V6 stage by multiplying times corn height in 2011, 2012 and over both years when using the GS (Table 3). Using the CC red NDVI data to calculate INSEY the significance of the relationship increased with the inclusion of corn height in 2011 and over both years. There was no difference in regression coefficient with crop height in 2012. The CC red-edge NDVI relationship increased at V6 with crop height in 2011, 2012 and over both years.

At the V12 stage in eastern medium-textured conventional-till sites, there was an improvement in the INSEY relationship with the GS and CC with both the red and red-edge options when corn height was applied in 2011. However, in 2012, none of the INSEY measurements were improved by applying corn height. Over the two years, there was a combined improvement in the INSEY/yield relationship with all instruments by applying corn height.

Eastern no-till sites relationships at the V6 stage for the GS and the CC with both red and red-edge were very low in both 2011 and 2012 (Table 4). There was no improvement when height was applied to the relationships. At V12, the INSEY relationships were highly significant with both sensors in 2011, but were not improved by the application of crop height. In 2012, the V12 relationships were not significant for all sensors. Since there were large differences in relationships between INSEY/INSEYH between 2011 and 2012, the data are not combined in Table 4. Rainfall from May 1 through September 15 in the region representing sites in 2011 received between 350 mm and 450 mm rainfall, while during the same time period in 2012 the rainfall ranged from 150 mm to 240 mm (NDAWN data (http://ndawn.ndsu.nodak.edu). Failure of early plant height measurements to improve the INSEY relationship (i.e. INSEYH) with yield in general in 2012 might be explained by early to mid-season plant height measurements that were favorable for higher yields than experienced, while yields were later suppressed at some locations by continued dry, hot weather. Eastern no-till sites residue should not interfere with growing corn reflection signatures because the wavelengths of absorption by residues are more similar to soil than they are to green plant tissue (Aase and Tanaka 1991). A possible cause of poor relationships at V6 with eastern no-till sites is the slower early corn growth in no-till sites fields (Hoeft et al. 1999). Early sensor readings may not have reflected the fertility of the plots and instead the growth of corn at the early stages was dominated by cooler and wetter soil conditions and generally poor growth. In these eastern no-till sites, a general yellowing of corn in all plots at V6 was observed that would have also resulted in lower red-edge sensor readings.

In eastern high clay conventional-till sites at the V6 stage, the GS had the greatest r^2 value compared to the two CC options in 2011 (Table 5). The GS and CC red and red-edge INSEY calculations improved with the application of corn height at V6 in 2011. At the V12 stage in 2011, the CC red-edge sensor had the greatest r^2 values in 2011and 2012. All sensors were improved with height in 2011, but not in 2012 or over both years. In 2011 at V12, there was improvement in the INSEY/yield relationships for both sensors when corn height was applied. However, in 2012 and in the combined data set for 2011-2012 there was a decrease in INSEY relationship with corn height. The lack of improvement with height in 2012 might be explained by the presence of early-season soil moisture in the eastern high clay conventional-till sites that resulted in early to mid-season corn heights that predicted higher than achieved yields. Yields were probably suppressed in these eastern high clay conventional-till sites by continued dry weather conditions through the summer.

Over all sites in 2011 at both V6 and V12 the INSEY relationship increased for both sensors with the application of corn height. In 2012, however, the INSEY relationship was generally not increased with crop height considered. After combining data over both years, the INSEY relationship was not increased with consideration of crop height (Table 6), probably again due to the drier weather during the 2012 growing season that resulted in over-estimation of corn yield.

4.5. Discussion

Partitioning soil texture and tillage system data revealed strengths and weaknesses of using crop height to increase the relationship between GBAO sensor readings and yield. In eastern medium-textured coventional-till sites, corn height improved the relationship of Gs and CC red and red-edge options at both V6 and V12 in 2011 and at the V6 stage in 2012. Over 2011 and 2012, corn height improved all relationships. In 2012 at V12 during the very dry summer, sensor readings did not predict corn yield well, resulting in lower sensor to yield relationships and lower regression coefficients when corn height was applied. In eastern high clay conventional-till sites in 2011, corn height improved the relationship with both sensors at V6 and V12, but did not improve the relationship in 2012 or in both years combined. A possible reason for poor sensor relationships in eastern high clay conventional-till sites in 2012 is the dry growing season weather. In the highly smectitic clays of the Red River Valley where the eastern high clay conventional-till sites were located, dry soil conditions and corresponding plant water uptake results in large, deep cracks that result in deep soil drying. Even though capillary movement of water should theoretically supply moisture to a corn crop in eastern high clay conventional-till sites textured soils, deep soil cracks result in dryer soil at deeper depths than otherwise possible (Whitmore and Whalley 2013). Deep soil cracks are not present in eastern medium-textured conventional-till sites during similar dry conditions.

In 2011 rainfall totals between April 1 and July 1 were about 100-mm higher than normal, combined with one of the largest snowmelts on record (NDAWN records, ndawn.ndsu.nodak.edu/). Most of the eastern high clay conventional-till sites were saturated with water, but not flooded for about 6 weeks. Early season denitrification from these locations was likely very high (van Es et al. 2007; Sogbedji et al. 2001). In contrast, eastern medium-textured coventional-till sites tended to dry between rains due to better internal drainage and N losses to denitrification were probably much lower. Differences in denitrification potential may be a reason why these soils needed to be separated in this data set, and why they may need to be separated in the future. Nicolas et al. (2012) also observed that N-rate data sets across a multi-state region were best analyzed and understood if the eastern high clay conventional-till sites that were subject to denitrification losses were analyzed separately from other soil textures. Similar confounding of the prediction from corn height with soil wetness was observed by Machado et al. (2002), who reported that plant height at V12 explained 61 % of the variations of corn yield in the dry year of 1998, but this relationship did not exist in the wet year of 1999.

Table 3.[††] Statistics of regression coefficients (r^2) of measured corn yield fertilized at six N rates as a function of INSEY (in-season estimate of yield) and INSEYH (in-season estimate of yield multiplied times height component) with corn yield using the GreenSeeker® sensor or the Holland Crop Circle® sensor at V6 and V12 growth stages in eastern medium-textured conventional-till sites under conventional tillage in 2011 and 2012. Regression models compared are exponential.

		2011				2012				2011 & 2012			
Growth		**INSEY†**		**INSEYH**		**INSEY**		**INSEYH**		**INSEY**		**INSEYH**	
stage	**Sensor type**	**r^2**	**Sig‡**	**r^2**	**sig**	**r^2**	**Sig**	**r^2**	**Sig**	**r^2**	**Sig**	**r^2**	**Sig**
V6	GreenSeeker®	0.49	***	0.76	***	0.46	***	0.48	***	0.53	***	0.63	***
	Crop Circle/red-edge	0.65	***	0.79	***	0.51	***	0.55	***	0.63	***	0.75	***
	Crop Circle/red	0.61	***	0.79	***	0.55	***	0.56	***	0.63	***	0.67	***
V12	GreenSeeker®	0.17	*	0.89	***	0.12	*	0.08	NS	0.13	**	0.28	***
	Crop Circle/red-edge	0.35	***	0.87	***	0.33	***	0.11	*	0.36	***	0.44	***
	Crop Circle/red	0.10	NS	0.43	***	0.35	***	0.11	*	0.24	***	0.35	***

† INSEY is: (NDVI / growing degree days from planting date). INSEYH is: (NDVI X corn height in centimeters) / growing degree days from planting). ‡* denotes significance at 0.001; ** denotes significance at 0.01; * denotes significance at 0.05. ††Data in the Table 3 has been taken from Sharma and Franzen, 2014.**

Table 4.[††] Statistics of regression coefficients (r^2) of measured corn yield fertilized at six N rates as a function of INSEY (in-season estimate of yield) and INSEYH (in-season estimate of yield with height component) with corn yield using the GreenSeeker® sensor or the Holland Crop Circle® sensor at V6 and V12 growth stages in eastern no-till sites in 2011 and 2012. Regression models compared are exponential.

		2011				2012			
		INSEY†		INSEYH		INSEY		INSEYH	
Growth stage	**Sensor type**	**r^2**	**Sig‡**	**r^2**	**sig**	**r^2**	**Sig**	**r^2**	**Sig**
V6	GreenSeeker®	0.05	NS	0.04	NS	0.08	NS	0.0	NS
	Crop Circle/red-edge	0.18	NS	0.03	NS	0.33	NS	0.0	NS
	Crop Circle/red	0.08	NS	0.01	NS	0.36	*	0.05	NS
V12	GreenSeeker®	0.68	***	0.44	**	0.02	NS	0.01	NS
	Crop Circle/red-edge	0.80	***	0.57	***	0.01	NS	0.0	NS
	Crop Circle/red	0.62	***	0.47	**	0.01	NS	0.005	NS

† INSEY is: (NDVI / growing degree days from planting date). INSEYH is: (NDVI X corn height in centimeters) / growing degree days from planting). ‡* denotes significance at 0.001; ** denotes significance at 0.01; * denotes significance at 0.05. [††]Data in the Table 4 has been taken from Sharma and Franzen, 2014.**

Table 5.†† Statistics of regression coefficients (r^2) of measured corn yield fertilized at six N rates as a function of INSEY (in-season estimate of yield) and INSEYH (in-season estimate of yield with height component) with corn yield using the GreenSeeker® sensor or the Holland Crop Circle® sensor at V6 and V12 growth stages in high-clay soils in 2011 and 2012. Regression models compared are exponential.

		2011				**2012**				**2011 & 2012**			
Growth		**INSEY†**		**INSEYH**		**INSEY**		**INSEYH**		**INSEY**		**INSEYH**	
Stage	**Sensor Type**	**r^2**	**Sig‡**	**r^2**	**sig**	**r^2**	**Sig**	**r^2**	**Sig**	**r^2**	**Sig**	**r^2**	**Sig**
V6	GreenSeeker®	0.40	***	0.49	***	0.60	***	0.41	***	0.53	***	0.35	***
	Crop Circle/red-edge	0.22	***	0.32	***	0.82	***	0.76	***	0.40	***	0.37	***
	Crop Circle/red	0.33	***	0.37	***	0.80	***	0.76	***	0.48	***	0.35	***
V12	GreenSeeker®	0.55	***	0.70	***	0.57	***	0.38	***	0.59	***	0.29	***
	Crop Circle/red-edge	0.73	***	0.78	***	0.73	***	0.27	***	0.69	***	0.37	***
	Crop Circle/red	0.59	***	0.72	***	0.66	***	0.22	***	0.70	***	0.20	***

† INSEY is: (NDVI / growing degree days from planting date). INSEYH is: (NDVI X corn height in centimeters) / growing degree days from planting). ‡* denotes significance at 0.001; ** denotes significance at 0.01; * denotes significance at 0.05. †† Data in the Table 5 has been taken from Sharma and Franzen, 2014.**

Table 6.[††] Statistics of regression coefficients (r^2) of measured corn yield fertilized at six N rates as a function of INSEY (in-season estimate of yield) and INSEYH (in-season estimate of yield with height component) with corn yield using the GreenSeeker® sensor or the Holland Crop Circle® sensor at V6 and V12 growth stages in all sites in 2011 and 2012. Regression models compared are exponential.

		2011				2012				2011 & 2012			
		INSEY†		INSEYH		INSEY		INSEYH		INSEY		INSEYH	
Growth Stage	Sensor Type	r^2	Sig‡	r^2	sig	r^2	Sig	r^2	Sig	r^2	Sig	r^2	Sig
V6	GreenSeeker®	0.20	***	0.34	***	0.26	***	0.27	***	0.25	***	0.25	***
	Crop Circle/red-edge	0.15	***	0.34	***	0.51	***	0.38	***	0.40	***	0.36	***
	Crop Circle/red	0.15	***	0.35	***	0.49	***	0.38	***	0.34	***	0.28	***
V12	GreenSeeker®	0.31	***	0.56	***	0.21	***	0.21	***	0.26	***	0.21	***
	Crop Circle/red-edge	0.47	***	0.65	***	0.25	***	0.18	***	0.46	***	0.30	***
	Crop Circle/red	0.29	***	0.57	***	0.19	***	0.16	***	0.27	***	0.18	***

† INSEY is: (NDVI / growing degree days from planting date). INSEYH is: (NDVI X corn height in centimeters) / growing degree days from planting). ‡* denotes significance at 0.001**. **[††]Data in the Table 6 has been taken from Sharma and Franzen, 2014.**

Sensing and height measurements were conducted in centimeters at V6 (six leaf stage of corn) and V12 (12 leaf stage of corn) stages. There was a 14-15 days interval between the two stages, therefore factors that could influence the N uptake or response will affect the relationship between the INSEY and INSEYH with yield. In addition, large differences in mineralization potentials of the soil were probable between the two very different years. In 2011, rainfall was very high during May and early June, resulting in N losses particularly in eastern high clay conventional-till sites. In contrast, 2012 was one of the driest eastern North Dakota growing seasons on record, beginning about July 2011 continuing through August 2012. Despite the wet conditions in 2011 and conversely dry conditions in 2012, corn yields were high within the experimental sites in both years (yield range in 2011 was 6.2 Mg ha^{-1} to 13.8 Mg ha^{-1}; yield range in 2012 was from 6.2 Mg ha^{-1} to 15 Mg ha^{-1}, data not shown). Lowest yields were experienced in both years in eastern high clay conventional-till sites due to wet soil conditions in 2011 and cooperators seeding too quickly in 2012 and the poor soil conditions that resulted. Consequently, improvement in r^2 value was observed at V12 sensing as compared to V6 under most eastern high clay conventional-till sites and eastern no-till sites each year and in combined years in eastern high clay conventional-till sites. Because of different amounts of available N to these sites as a result of different soil texture and weather conditions, plant height and yield relationships were different across sites, therefore, the r^2 value varied across the locations and years. Differences in the seasonal rate of GDD accumulation, as well as rainfall, probably influenced N response of corn, which would have directly affected the yield and sensor relationship (Nicolas et al. 2012).

Although the relationship between yield and INSEY was not improved in all sites in all years, a significant relationship was recorded between yield and INSEYH at V6 and V12 across two years under eastern medium-textured conventional-till sites and high-clay conventionally tilled soils (Table 3 and Table 5). Similar results were reported by Katsvairo et al. (2003) who observed that two out of three locations in 2000 and at one out of three locations in 2001, plant heights at V6 were correlated with yields. Similarly, plant height was correlated with corn yields at V10 in their study at three locations in 2000 but at only one location in 2001.

It is also important to note that though neither GS nor CC sensors, nor addition of corn height always resulted in significant yield prediction at both growth stages over all categories of plots, the alternative of guessing at in-season N rates is also not desirable. Growers who adopt an in-season corn N application strategy that uses one or all of these technologies in the future will have at least avoided a sensitive N loss time period by delaying a portion of their N fertilizer requirements until later in the season. In addition, a more scientific approach using the comparative health of the crop at the date of sensing to direct in-season application of N is probably more desirable than a pre-season guess regarding N rate; a rate that is often guided by historical rates, neighbors rates, rates the grower read about in a farm magazine or the over-optimistic recommendations of an aggressive supplier representative.

4.6. Conclusion

The GS sensor using the red/NIR bands and the CC using both red and red-edge NDVI options were useful in both medium texture and eastern high clay conventional-till sites for yield prediction. Multiplying the sensor reading INSEY by crop height often increased the yield prediction relationship. During the dry year of 2012, the sensors and height were least useful in the eastern no-till sites, as was the sensor and height measurements at V6 in 2011. Slow growing conditions and general plant yellowing during the wet early season of 2011 probably was the cause of the poor sensor/yield relationships. At V12, the eastern no-till sites sensor relationships in 2011 were significant for all sensors, although height did not improve the relationship. In general, the height addition to sensor readings was most helpful at V6 and V12 stage for the GS and for CC using the red NDVI option. Although crop height improved the CC red-edge NDVI relationship with yield sometimes, the frequency of improvement was less than with the CC red NDVI option or the GS. This tendency is logical, since the red/NIR relationships produced by both the GS and CC red NDVI tend to provide a two-dimensional reading measurement of crop canopy, whereas the CC red-edge sensor reads more like the human eye in detection of greenness of the crop. The frequency of improvement suggests that algorithms using the GS or CC red NDVI would be improved with incorporation of a height measurement. Although the height measurements in these experiments were conducted manually, commercial adoption of algorithms that include height will require automated means for accumulating partner height data along with simultaneous collection of sensor readings.

4.7. Literature Cited

Aase, J.K., and D.L. Tanaka. 1991. Reflectances from four wheat residue cover densities as influenced by three soil backgrounds. Agron. J. 83:753-757.

Biermacher, J.T., F.M. Epplin, B.W. Brorsen, J.B. Solie, and W.R. Raun. 2006. Maximum benefit of aprecise nitrogen application system for wheat. Precis. Agric. 7:1–12.

Chung, B., K. Girma, K.L. Marin, B.S. Tubana, D.B. Arnall, and O. Walsh. 2008. Determination of optimum resolution for predicting corn grain yield using sensor measurements. Arch. Agron. Soil Sci.54:481-491.

Franzen, D. W. 2010. North Dakota fertilizer recommendation tables and equations. NDSU Ext. Circ. SF-882. North Dakota State University Extension Service, Fargo, ND.

Franzen, M. 2012. Program for initial analysis of GreenSeeker® and Holland Crop Circle® Sensor raw data within Excel. Unpublished program. Fargo, ND.

Franzen, D.W., G. Wagner, and A. Sims. 2003. Application of a ground-based sensor to determine N credits from sugarbeet. In Sugarbeet Research and Extension Reports. (Vol. 34, pp. 119-123) Sugarbeet Research and Education Board of Minnesota and North Dakota. Fargo, ND.

Freeman, K.W., K. Girma, D.B. Arnall, R.W. Mullen, K.L. Martin, and R.K. Teal. 2007. By-plant prediction of corn forage biomass and nitrogen uptake at various growth stages using remote sensing and plant height. Agron. J. 99:530-536.

Gitelson, A.A., Y.J. Kaufman, and M.N. Merzlyak. 1996. Use of a green channel in remote sensing of global vegetation from EOS-MODIS. Remote Sens. Environ. 58:289-298.

Hoeft, R.G., E.D. Nafziger, L.C. Gonzini, J.J. Warren, E.A. Adee, and L.E. Paul. 1999. Strip till tillage, N placement, and starter fertilizer effects on corn growth and yield. In Illinois Fert. Con. Pro. On line at http://frec.ifca.com/1999/report4 .

Holland, K.H., and J.S. Schepers. 2010. Derivation of a variable rate nitrogen application method for in-season fertilization of corn. Agron. J. 102:1415-1424.

Holland, K.H., and J.S. Schepers. 2014. Use of virtual reference concept to interpret active crop canopy sensor data. Precis. Agric. 14:71-85.

Horler, D.N.H., M. Dockray, J. Barber, and A.R. Barringer. 1983. Red-edge measurements for remotely sensing plant chlorophyll content. Adv. Space Res. 3:273-277.

Haboudane, D., J.R. Miller, E. Pattey, P.J. Zarco-Tejada, and I.B. Strachan. 2004. Hyperspectral vegetation indices and novel algorithms for predicting green LAI of crop canopies: Modeling and validation in the context of precision agriculture. Remote Sens. Environ. 90:337-352.

Hussain, I., K.R. Olson, and S.A. Ebelhar. 1999. Impacts of tillage and no-till on production of maize and soybean on an eroded Illinois silt loam soil. Soil Tillage Res. 52:37–49.

IDRE-USDA. 2013. SAS FAQ: How do I compare regression coefficients between two groups? http://www.ats.ucla.edu/stat/sas/faq/compreg2.htm .

Kapusta, G., R.F. Krausz, and J.L. Matthews. 1996. Corn yield is equal in conventional, reduced, and no tillage after 20 years. Agron. J. 88:812–817.

Katsvairo T.W., W.J. Cox, and H.M. Van Es. 2003. Spatial growth and nitrogen uptake variability of corn at two nitrogen levels. Agron. J. 95:1000–1011.

Kladivko, E.J., D.R. Griffith, and J.V. Mannering. 1986. Conservation tillage effects on soil properties and yield of corn and soya beans in Indiana. Soil Tillage Res. 8:277–287.

Lindsay, W. L., and W.A. Norvell. 1978. Development of a DTPA soil test for zinc, iron, manganese, and copper. Soil Sci. Soc. Am. J. 42:421-428.

Machado, S., E.D. Jr. Bynum, T.L. Archer, R.J. Lascano, L.T. Wilson, and J. Bordovsky. 2002. Spatial and temporal variability of corn growth and grain yield: Implications for site-specific farming. Crop Sci. 42:1564-1576.

Martin, K., W. Raun, and J. Solie. 2012. By-plant prediction of corn grain yield using optical sensor readings and measured plant height. J. Plant Nutr. 35:1429-1439.

Myneni, R.B., R.R. Nemani, and S.W. Running. 1997. Estimation of global leaf area index and absorbed PAR using radiative transfer models. T. Geo. Remote Sens. 33:1380-1393.

Nicolas T., Y.M. Bouroubi, C. Bélec, R.W. Mullen, N.R. Kitchen, and W.E. Thomason. 2012. Corn response to nitrogen is influenced by soil texture and weather. Agron. J. 104:1658–1671.

Olsen, S.R., C.V. Cole, F.S. Watanabe, and L.A. Dean. 1954. Estimation of available phosphorus in soils by extraction w ith sodium bicarbonate. USDA Circular 939. U.S. Government Printing Office, Washington D.C.

Ortiz-Monasterio, J.I., and W.R. Raun. 2007. Reduced nitrogen and improved farm income for irrigated spring wheat in the Yaqui Valley, Mexico, using sensor based nitrogen management. J. Agric. Sci. 145:1–8.

Payero, J.O., C.M.U. Neale, and J.L. Wright. 2004. Comparison of eleven vegetation indices for estimating plant height of alfalfa and grass. Am. Soc. Agric. Eng. 20:385-393.

Raun, W.R., and J.S. Schepers. 2008. Nitrogen management for improved efficiency. In J. S. Schepers & W. R. Raun (Eds.), Nitrogen in Agricultural Systems (Agronomy Monograph No. 50, pp. 675-694). ASA-CSSA-SSSA, Madison, WI.

Raun, W.R., J.B. Solie, J.B., G.V. Johnson, M.L. Stone, E.V. Lukina, and W.E. Thompson. 2001. Agron. J. 93:131-138.

Raun, W.R., J.B. Solie, M.L. Stone, K.L. Martin, K.W. Freeman, and R.W. Mullen. 2005. Optical sensor-based algorithm for crop nitrogen fertilization. Commun. Soil. Sci. Plant Anal. 36:2759-2781.

Raun, W.R., J.B. Solie, and M.L. Stone. 2011. Independence of yield potential and crop nitrogen response. Precis. Agric. 12:508-518.

Schepers, J.S., and K.H. Holland. 2012. Evidence of dependence between crop vigor and yield. Precis. Agric. 13:276-284.

Schulte, E.E., and B.G. Hopkins. 1996. Estimation of soil organic matter by weight-loss-on ignition. *In* F. R. Magdoff et al. (Eds.), Soil Organic Matter: Analysis and Interpretation (Chap. 3, pages 21-31). SSSA Spec. Publ. 46, SSSA, Madison, Wis.

Sharma, L.K., and D.W. Franzen, 2014. Use of corn height to improve the relationship between active optical sensor readings and yield estimates. Precis. Agric. Online publication.

Shrestha, D.S., B.L. Steward, S.J. Birrell, and T.C. Kaspar. 2002. Plant height estimation using two sensing systems. T. Am. Soc. Agric. Eng. CD-ROM. St. Joseph, MI.

Sogbedji, J.M., H.M. van Es, S.D. Klausner, D.R. Bouldin, and W.J. Cox. 2001. Spatial and temporal processes affecting nitrogen availability at the landscape scale. Soil Tillage Res. 58:233–244.

Teal, R.K., B. Tubana, K. Girma, K.W. Freeman, D.B. Arnall, and O. Walsh. 2006. In-season prediction of corn grain yield potential using normalized difference vegetation index. Agron. J. 98:1488–1494.

Thomas, G.W. 1982. Exchangeable cations. In A. L. Page et al. (Eds.). Methods of soil analysis. Part 2. (Agronomy Monographs 9, pp. 159-165). ASA and SSSA, Madison, Wis.

Tubana, B.S., D.B. Arnall, O. Walsh, B. Chung, J.B. Solie, and K. Girma. 2008. Adjusting midseason nitrogen rate using a sensor-based optimization algorithm to increase use efficiency in corn. J. Plant Nutr. 31:1393–1419.

Vanderlip, R.L., and D.L. Fjell. 1994. Use of growing degree units in corn production. In Corn Production Handbook (pp. 6-8). Kansas State Univ. Agri. Exp. Sta. and Coop. Ext. Serv. C-560. Manhattan, KS.

van Es, H.M., C.L. Yang, and L.D. Geohring. 2005. Maize nitrogen response as affected by soil type and drainage variability. Precis. Agric. 6:281–295.

Watson, D., and J.R. Brown. 1998. pH and lime requirement. In J. R. Brown (Ed.) Recommended Chemical Soil Test Procedure for the North Central Region (p. 13). North Central Regional Res. Pub. No. 221 (revised). Missouri Agric. Exp. Stat. SB 1001, Univ. of Missouri, Columbia.

Whitmore, A.P., and W.R. Whalley. 2013. Physical effects of soil drying on roots and crop growth. J. Exp. Bot. 60:2845-2857.

Wilhelm, W., K. Ruwe, and M.R. Schlemmer. 2000. Comparison of three leaf area index meters in a corn canopy. Publication from USDA-ARS/UNL Faculty Paper 71. http://digitalcommons.unl.edu/usdaarsfacpug/71

Yin, X., N. Jaja, M.A. McClure, and R.M. Hayes. 2011a. Comparison of models in assessing relationship of corn yield with plant height measured during early- to mid-season. J. Agric. Sci. 3:14-24.

Yin, X., M.A. McClure, N. Jaja, D.D. Tyler, and R.M. Hayes. 2011b. In-season prediction of corn yield using plant height under major production systems. Agron. J. 103:923-929.

CHAPTER V. COMPARISON OF TWO GROUND-BASED ACTIVE-OPTICAL SENSORS FOR IN-SEASON ESTIMATION OF CORN (*ZEA MAYS,* L) YIELD

5.1. Abstract

Thirty field experiments were conducted in North Dakota during 2011 and 2012 to compare two ground-based active-optical sensors for their relationship between sensor readings and INSEY (in-season estimate of yield). The experimental design at each site was a randomized complete block with four replications and six N rate treatments: control, 45, 90, 134, 179, and 224 kg ha^{-1} applied pre-plant as ammonium nitrate within five days of planting. The two sensors, GS and CC were used to scan over the top of the corn at V6 and V12 growth stages. The GS INSEY and the CC INSEY were similarly related to corn yield at V6. The CC using the red-edge lens option improved the INSEY relationship to corn yield compared to the GS or the CC using the red lens option at V12.

Key Words: Canopy sensor, INSEY, nitrogen

5.2. Introduction

Corn (*Zea mays,* L.) is an important crop in North Dakota and it is used mainly as livestock feed and in fuel ethanol production. According to the USDA National Agriculture Statistics, approximately 1.008 million hectares of corn was planted in North Dakota in 2012, with yields ranging from 5 to 10.6 Mg ha^{-1}. Nitrogen (N) use efficiency (NUE) has been widely used as a metric to relate nitrogen uptake by crop with the N supplied to the crop. World cereal production NUE has been estimated at about 33% (Raun and Johnson, 1999). Causes of low NUE include loss through the nitrate leaching and denitrification. Nitrogen losses from farm fields have been implicated in ground and surface water contamination, particularly in Corn Belt of the USA (Schilling, 2002; Steinheimer et al., 1998; Cast, 1999).

Within a field, corn growth rate and biomass accumulation varies spatially during the growing season. Some of the variability in growth is due to variable N supply. Spatial and temporal variability of N supply may be the result of crop management practices and local microclimates (Blackmer et al., 1997). Yield variability is the result of the combined variability in soil texture, landscape, crop yield history, soil physical and chemical properties, and nutrient availability (Wibawa et al., 1993; Penny 1996). Fields or parts of fields with coarse soil textures are susceptible to N leaching losses, while areas with fine texture in certain climates may experience losses due to denitrification.

During the first 30 to 45 days after corn planting, corn only takes up five to ten percent of the total N required for the growing season. However, many growers apply all of their N preplant, which exposes much of the N applied to early season losses. Transitioning to a side-dress system allows corn growers to avoid the first month of N loss vulnerability and also allows for the use of a sensor-based approach to direct N rates at the time of side-dress application. Remote sensing using optical light sensors can be used to predict the yield potential of crop (Lillesand and Kiefer, 1994). Remote sensors helped to improve crop yield where inputs were adjusted based on sensor reading for water and nutrients (Evans and Fisher, 1999). A variety of indexes have been used to related sensor reading to crop health and biomass or yield, including the Red/Near-infrared simple ratio (R/NIR) and the normalized difference vegetation index (NDVI) The NDVI is preferred for satellite images, for example, due to its relative insensibility to variations in light through layers of the atmosphere. The simple ratio has been found to be a good indicator for ground-based measurements. The NDVI has also been used to estimate the winter wheat (*Triticum aestivum* L.) yield potential at the Feekes 4 to Feekes 6 growth stage using the INSEY index (Raun et al., 2002). The NDVI index along with the R/NIR simple ratio has been used to estimate leaf area index, green biomass, crop yield potential, and crop photosynthetic capacity (Araus, 1996). Several studies have been conducted recently to help develop the use of ground-based active-optical sensors (GBAO) for commercial agriculture. A good relationship between spectral reflectance and N status in green vegetation of the crop has been shown (Stone et al., 1996; Bausch and Duke, 1996; Osborne et al., 2002; Blackmer et al., 1996a).

Two commercially available (2013) GBAO sensors are the GS and CC. Since different wavelengths are emitted and received by the two sensors that may result in different sensor reading results, it was the objective of these studies to compare the GS and the CC in their ability to estimate corn yield.

5.3. Material and Methods

Thirty grower field sites were used to conduct N-rate trials in corn during the 2011 and 2012 growing seasons (Table 7) in southeastern North Dakota. Thirteen field experiments were conducted in 2011 and seventeen in 2012. Each site was part of a larger field operated by a farmer cooperator using their seed corn hybrid, their planter, and all other field operations with the exception of the N application. Sites were located prior to field work in conventional till fields. Each field site consisted of a randomized complete block design with four blocks and six N treatments; check (no added N), 90, 135, 189 and 224 kg N ha^{-1} were hand applied in the form of ammonium nitrate granules. A large flag, about 1.5-m in height with 0.5-m square bright orange plasticized fabric was placed at each site corner to let the commercial fertilizer applicator or farmer know where to avoid additional N applications. Corners were geo-referenced using a Trimble Nomad® handheld GPS instrument. A 5-cm diameter steel washer was buried about 15-cm deep at each corner. After planting, the field was revisited and the corners were found using the GPS Nomad and a Garrett AT PRO® metal detector (Garrett Electronics, Inc., Garland, TX, USA). Each experimental unit was 6.1-m in length and 3.05-m in in width. An examination of the yield response of the sites to N through a multiple regression analysis indicated that eastern high clay conventional-till sites (those whose clay content was greater than 30 percent) responded differently to N compared to lower clay sites (eastern medium-textured coventional-till sites). Similarly, sites that had been in eastern no-till sites/one-pass seeding tillage system (greater than six consecutive years) responded differently to N rate compared to conventionally tilled locations. The results strongly suggested that yield responses to N in this data set were dissimilar for eastern high clay conventional-till sites and other soil textures and also for eastern no-till sites compared to conventionally tilled sites (data not shown). Based on textural analysis, all the locations were classified into eastern high clay conventional-till sites and eastern medium-textured coventional-till sites soil types. The sites were also classified into eastern no-till sites and conventional tillage categories (Table 8).

Two handheld GBAO sensors were used in the study: GS and CC. The CC sensor simultaneously emits three bands from light emitting diodes; visible (670 nm), red-edge (730 nm) and near infrared (NIR, 760nm). The reflected light strikes companion detectors sensitive to the emitted wavelengths. The CC sensors were calibrated using software provided by Holland Scientific. Absorption measurements were obtained at a rate of ten measurements per second for these experiments. At a height above the crop canopy of about 75 cm, the width of light output was about 42 cm.

The GS used in the study emits two wavebands of light; 660 ± 15nm (red) and 770 ± 15 nm (NIR). Light is emitted from diodes in alternate bursts: the red source and the NIR source pulse for 1 msec at 40,000 Hz. Each burst amounts to about 40 pulses before pausing for the other diode to emit its radiation (another 40 pulses). The illuminated area is approximately 37 cm wide at a height above an object of about 75 cm. The width of the light source is relatively constant for sensor heights between 60 and 120 cm above the canopy. Outputs from the sensor are a normalized difference vegetative index (NDVI).

The GS readings and CC readings were obtained when the corn was about V6 stage and again about 2 weeks later when the corn reached V12. Readings were obtained over the top of the corn whirls on the identical interior row of each plot where harvest was intended.

The GS measurement was:

Red NDVI = (770 nm – 660 nm) / (770 nm + 660 nm),

The CC measurement was:

Red NDVI = (760 nm – 670 nm) / (760 nm + 670 nm)

Red-edge NDVI = (760 nm – 730 nm) / (760nm+730nm)

The red-edge wavelength measurement differs from the red NDVI measurement because it measures plant chlorophyll content (Horler et al., 1983). The GS and CC readings consisted of a mean of between 30-50 individual readings from each plot. Means within a treatment were determined using in-house programs for GS and CC raw data developed for Excel (Franzen, 2012). Means for each N treatment sensor readings and yield were calculated using SAS 9.1 for windows. The value for sensor reading and corn height was calculated using the sensor reading multiplied by the corn height in centimeters.

Plant height was obtained from three representatively selected plants in the central row of each plot. A tape measure was used to measure corn height from the soil surface to about 5 centimeters above the corn whirl base. The height was measured at V6 and V12 leaf stage of the crop on the same day as sensing was carried out. The three measurements were averaged to provide the corn height for each plot.

Table 7. Global Positioning System coordinates and type of soil used for thirty field experiments in 2011 and 2012.

Year	Locations	GPS coordinates	Soil Type†
2011	Valley City	46° 52' 49.090" N, 97° 54' 46.240" W	Fine-loamy, mixed, superactive, frigid Calcic Hapludolls
	Rutland	45° 59' 58.051" N, 97° 28' 43.634" W	Fine-loamy, mixed, superactive, frigid Pachic Argiudolls
	Havana	45° 56' 04.266" N, 97° 35' 54.633" W	Fine-silty, mixed, superactive, frigid Pachic Hapludolls
	Durbin	46° 51' 29.495" N, 97° 09' 26.907" W	Fine, smectitic, frigid Typic Epiaquerts
	Mooreton	46° 12' 40.420" N, 96° 46' 43.259" W	Fine, smectitic, frigid Typic Epiaquerts
	Great Bend	46° 07' 54.977" N, 96° 43' 11.481" W	Fine, smectitic, frigid Typic Natraquerts
	Fairmount	45° 59' 39.021" N, 96° 35' 46.219" W	Fine-loamy, mixed, superactive, frigid Aeric Calciaquolls
	Christine	46° 53' 30.423" N, 96° 54' 05.749" W	Fine, smectitic, frigid Typic Epiaquerts
	Prosper	46° 56' 55.978" N, 97° 02' 48.344" W	Fine, smectitic, frigid Typic Calciaquerts
	Milnor	46° 16' 34.108" N, 97° 28' 02.389" W	Sandy, mixed, frigid Oxyaquic Hapludolls
	Page site 2	47° 09' 36.755" N, 97° 25' 48.088" W	Fine-loamy, mixed, superactive, frigid Calcic Hapludolls
	Buffalo	46° 56' 51.974" N, 97° 28' 01.950" W	Fine-loamy, mixed, superactive, frigid Calcic Hapludolls
	Page site 1	47° 09' 05.282" N, 97° 23' 21.552" W	Coarse-loamy, mixed, superactive, frigid Pachic Hapludolls
	Walcott	46° 30' 02.183" N, 97° 02' 32.182" W	Coarse-loamy, mixed, superactive, frigid Aquic Pachic Hapludolls
	Arthur	47° 03' 43.560" N, 97° 08' 04.248" W	Coarse-silty, mixed, superactive, frigid Aeric Calciaquolls
2012	Rutland East	45° 59' 36.599" N, 97° 27' 28.969" W	Fine-loamy, mixed, superactive, frigid Pachic Argiudolls
	Rutland west	45° 59' 32.671" N, 97° 30' 15.115" W	Fine-silty, mixed, superactive, frigid Aeric Calciaquolls
	Leonard-North	46° 42' 04.081" N, 97° 16' 52.371" W	Fine-silty, mixed, superactive, frigid Aeric Calciaquolls
	Casselton North	46º56’ 12.417” N, 97º 17’ 00.351”W	Fine-silty, mixed, superactive, frigid Aeric Calciaquolls
	Amenia	47° 00' 13.913" N, 97° 12' 57.025" W	Coarse-silty, mixed, superactive, frigid Aeric Calciaquolls
	Casselton South	46° 56' 26.922" N, 97° 17' 00.351" W	Fine, smectitic, frigid Typic Epiaquerts
	Galchutt	46° 23' 00.519" N, 96° 43' 48.576" W	Fine, smectitic, frigid Typic Natraquerts

(continues)

Table 7. Global Positioning System coordinates and type of soil used for thirty field experiments in 2011 and 2012 (continued)

Year	**Locations**	**GPS coordinates**	**Soil Type**[†]
2012	Fairmount North	45° 59' 38.268'' N, 96° 38' 18.155'' W	Coarse-silty, mixed, superactive, frigid Aeric Calciaquolls
	Fairmount South	45° 57' 23.964'' N, 96° 34' 35.244'' W	Fine-loamy, mixed, superactive, frigid Aeric Calciaquolls
	Great Bend	46° 08' 20.469'' N, 96° 44' 09.026'' W	Fine, smectitic, frigid Typic Natraquerts
	Prosper	46° 58' 10.307'' N, 96° 59' 20.466'' W	Fine, smectitic, frigid Typic Epiaquerts
	Barney	46° 10' 58.074'' N, 96° 55' 43.331'' W	Fine, smectitic, frigid Typic Epiaquerts
	Mooreton	46° 18' 13.407'' N, 96° 51' 40.672'' W	Coarse-loamy, mixed, superactive, frigid Aeric Calciaquolls
2013	Gardner	47° 09' 57.820'' N, 97° 02' 59.152'' W	Fine, smectitic, frigid Vertic Argialbolls
	Arthur	47° 06' 25.800'' N, 97° 14' 36.562'' W	Fine, smectitic, frigid Vertic Argialbolls
	Wheatland	46° 55' 06.854'' N, 97° 23' 14.391'' W	Fine-loamy, mixed, superactive, frigid Aeric Calciaquolls
	Milnor	46° 13' 11.317'' N, 97° 25' 31.110'' W	Fine-loamy, mixed, superactive, frigid Pachic Argiudolls
	Leonard South	46° 40' 32.061'' N, 97° 17' 02.579'' W	Sandy, mixed, frigid Typic Endoaquolls
	Walcott west	46° 30' 29.560'' N, 97° 03' 00.760'' W	Coarse-loamy, mixed, superactive, frigid Aeric Calciaquolls
	Walcott east	46° 29' 44.107'' N, 96° 53' 04.456'' W	Coarse-silty over clayey, mixed over smectitic, superactive, frigid Aeric Calciaquolls

† information collected from Soil Survey Staff, 2013

Table 8. Cultivation system, corn planting date, and the date of the first and second sensing of each of the thirty locations in 2011 and 2012.

Year	Locations	Tillage/Soil Type	Planting Date	1st Sensing	2nd Sensing
2011	Valley City	Eastern no-till sites	05/10/11	06/24/11	07/14/11
	Rutland	Eastern no-till sites	05/19/11	06/30/11	07/14/11
	Havana	Eastern no-till sites	05/17/11	06/30/11	07/14/11
	Durbin	Eastern high clay conventional-till sites	05/08/11	06/20/11	07/13/11
	Mooreton	Eastern high clay conventional-till sites	05/17/11	07/01/11	07/13/11
	Great Bend	Eastern high clay conventional-till sites	05/13/11	06/20/11	07/13/11
	Fairmount	Eastern high clay conventional-till sites	06/04/11	07/12/11	07/26/11
	Christine	Eastern high clay conventional-till sites	05/19/11	07/01/11	07/19/11
	Prosper	Eastern high clay conventional-till sites	05/25/11	07/06/11	07/18/11
	Milnor	Eastern medium-textured coventional-till sites	05/16/11	06/30/11	07/14/11
	Page site 2	Eastern medium-textured coventional-till sites	05/19/11	07/05/11	07/18/11
	Buffalo	Eastern medium-textured coventional-till sites	05/18/11	07/06/11	07/18/11
	Page site 1	Eastern medium-textured coventional-till sites	05/19/11	07/05/11	07/18/11
	Walcott	Eastern medium-textured coventional-till sites	05/18/11	07/01/11	07/19/11
	Arthur	Eastern medium-textured coventional-till sites	05/17/11	07/05/11	07/18/11
2012	Rutland east	Eastern no-till sites	05/17/12	06/11/12	06/25/12
	Rutland west	Eastern no-till sites	05/01/12	06/11/12	06/25/12
	Leonard-North	Eastern high clay conventional-till sites	04/26/12	06/12/12	06/25/12
	Casselton North	Eastern high clay conventional-till sites	04/22/12	06/12/12	06/25/12
	Armenia	Eastern high clay conventional-till sites	04/09/12	06/04/12	06/25/12
	Casselton South	Eastern high clay conventional-till sites	04/22/12	06/12/12	06/25/12
	Galchutt	Eastern high clay conventional-till sites	05/09/12	06/13/12	06/26/12
	Fairmount West	Eastern high clay conventional-till sites	04/26/12	06/11/12	06/26/12
	Fairmount south	Eastern high clay conventional-till sites	05/09/12	06/11/12	06/26/12
	Great Bend	Eastern high clay conventional-till sites	05/11/12	06/13/12	06/26/12
	Prosper	Eastern high clay conventional-till sites	04/24/12	06/12/12	06/25/12

(continues)

Table 8. Cultivation system, corn planting date, and the date of the first and second sensing of each of the thirty locations in 2011 and 2012 (continued)

Year	Locations	Tillage/Soil Type	Planting Date	1st Sensing	2nd Sensing
2012	Barney	Eastern high clay conventional-till sites	04/30/12	06/11/12	06/26/12
	Mooreton	Eastern medium-textured coventional-till sites	04/24/12	06/11/12	06/26/12
2013	Gardner	Eastern medium-textured coventional-till sites	04/25/12	06/12/12	06/25/12
	Arthur	Eastern medium-textured coventional-till sites	04/23/12	06/04/12	06/25/12
	Wheatland	Eastern medium-textured coventional-till sites	04/16/12	06/12/12	06/25/12
	Milnor	Eastern medium-textured coventional-till sites	04/15/12	06/13/12	06/25/12
	Leonard South	Eastern medium-textured coventional-till sites	04/09/12	06/12/12	06/25/12
	Walcott west	Eastern medium-textured coventional-till sites	04/30/12	06/11/12	06/25/12
	Walcott east	Eastern medium-textured coventional-till sites	04/26/12	06/13/12	06/25/12

Due to differences in farmer row width, plots consisted of between four rows in a 75 cm row width to six rows in a 50 cm row width. Alleyways were cut between experimental blocks when the corn was in V8. Although the corn plant nearest the alleyway at each end was usually larger than the ears further in the plot area, all ears were harvested, since all plants were subjected to sensor readings. One of the interior rows (6.1-m in length) was hand harvested, dried to about 10 percent moisture and then shelled using an Almaco® corn sheller in 2011. Moisture at shelling was determined on a grain subsample using a Dickey-John® moisture-test weight instrument. In 2012, a newer model Almaco corn sheller was used that allowed complete shelling of wet corn, so corn was shelled directly out of the field without a need for drying. Moisture was measured on shelled grain using the same instrument as in 2011.

Regression analyses was conducted on sensor readings and yield with yield as dependent variable INSEY and INSEYH were determined at V6 and V12 as the independent variable to evaluate the relationship between yield and INSEY multiplied with plant height at V6 and V12, respectively. To assess the relationship, linear, quadratic, square root, logarithmic, and exponential models were considered. The exponential model proved to most consistently represent the relationships. Conceptually, relationships between measurements at different growth stages of corn before the reproductive stage might be represented best by an exponential model (Vanderlip and Fjell, 1994). Regressions analyses were conducted on data from eastern no-till sites, eastern medium-textured coventional-till sites, and eastern high clay conventional-till sites.

The regression coefficient (r^2) value was used to evaluate the relationship of crop yield and sensor reading and crop yield with sensor reading multiplied with corn height at V6 and V12. All statistical analysis was conducted using SAS for Windows 9.2 (SAS Institute, Cary, NC). To evaluate differences between regression coefficient values, a regression ANOVA procedure was utilized as described by UCLA-IDRE using SAS (IDRE-UCLA, 2013). Comparisons were made using this procedure of regression coefficients between sensor readings with and without height considered, and between different sensor readings. Statements regarding whether regression coefficients are greater, less than, or similar to another are made with reference to these statistical procedures.

The formula for INSEY using either the GS or the CC was:

INSEY = (sensor reading) / (growing degree days from date of planting)

Soil was sampled from each site before start of the fieldwork. Eight cores of soil samples were taken by using a 2.5-cm diameter hand probe from 0- 15 cm depth for the analysis of potassium, phosphorous, zinc, pH, and organic matter. A depth of 0-60 cm was used for residual nitrate analysis. If nutrients other than N were required within the plot area and the cooperator was not able to apply them, the nutrients were applied by the researchers on the same day as the N treatments based on recommended rates from Franzen (2010). Soil samples were air-dried, ground to pass through a 2-mm screen and thoroughly mixed before analysis. Soil pH was measured using a 1:1 soil: deionized H_2O solution method (Watson and Brown 1998). Organic matter was determined using the loss following ignition method (Schulte and Hopkins 1996); phosphorus was analyzed using the Olsen method (Olsen et al., 1954). Potassium was analyzed using the 1-N ammonium acetate method (Thomas 1982) and the DTPA method (Lindsay and Norvell 1978) was used for determination of plant available zinc.

5.4. Results

Corn yield generally increased with fertilizer N application rate at all locations as well as within categories compared to the control (Figs. 2, 3, and 4). Higher yields were often obtained under the eastern medium-textured coventional-till sites. Yield within the eastern high clay conventional-till sites site category generally maximized at the 179 kg ha^{-1} rate, while the medium texture site category and the eastern no-till sites category sites generally maximized yield at the 135 kg ha^{-1} rate.

The relationship between INSEY and yield at V6 stage was significant for both the GS and CC Red NDVI and CC Red-edge NDVI in the eastern medium-textured coventional-till sites category under conventional tillage (Table 9). The relationship between INSEY and yield under eastern medium-textured coventional-till sites was higher with the CC red-edge NDVI as compared to GS and CC red NDVI at V12 (Table 3).

In the eastern no-till sites site category, the INSEY to yield relationship for both sensors was significant at the V12 stage in 2011, but not in 2012 (Table 10). Because the relationship between years was very different in 2011 compared to 2012, a combined analysis was not conducted. The lack of INSEY relationship to yield in 2011 and 2012 at the V6 stage might be explained by slow early corn growth in each year under eastern no-till sites compared to the conventional tillage sites. At V12 in 2011, the prediction of yield was improved, probably because the earlier detrimental effects of residue cover were diminished with time and soil warming. In 2012, however, abnormally dry soil conditions beginning in mid-July of 2011 resulted in over estimation of corn yield at both sensing periods compared to achieved yields at most sites.

Within the eastern high clay conventional-till sites category (Table 11) and all categories combined (Table 12), the relationship between INSEY and yield was significant at both the V6 stage and the V12 stage. The INSEY and yield relationship of both sensors was higher at V12 stage during 2011 as compared to 2012 and all sites together. The CC red-edge INSEY was generally better related to yield at V12 during 2011 (Table 5 and Table 6). CC Red NDVI was similar to the GS Red NDVI in predicting yield.

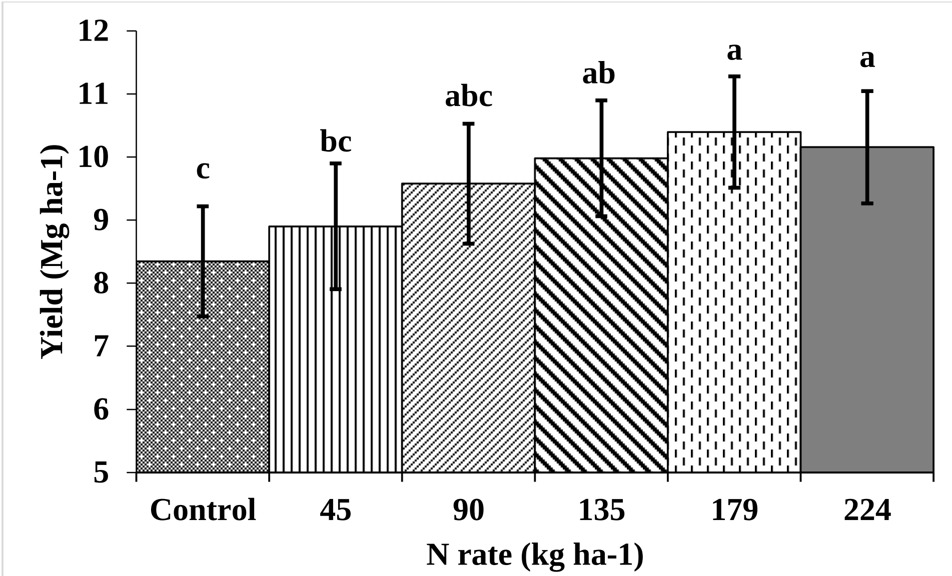

Fig. 2. Corn yield within the eastern high clay conventional-till sites category, 2011 and 2012 combined, in response to N fertilizer rates. Shaded bars indicate corn yield. Bars with similar letters imposed above are not significantly different from each other at *P* < 0.05.

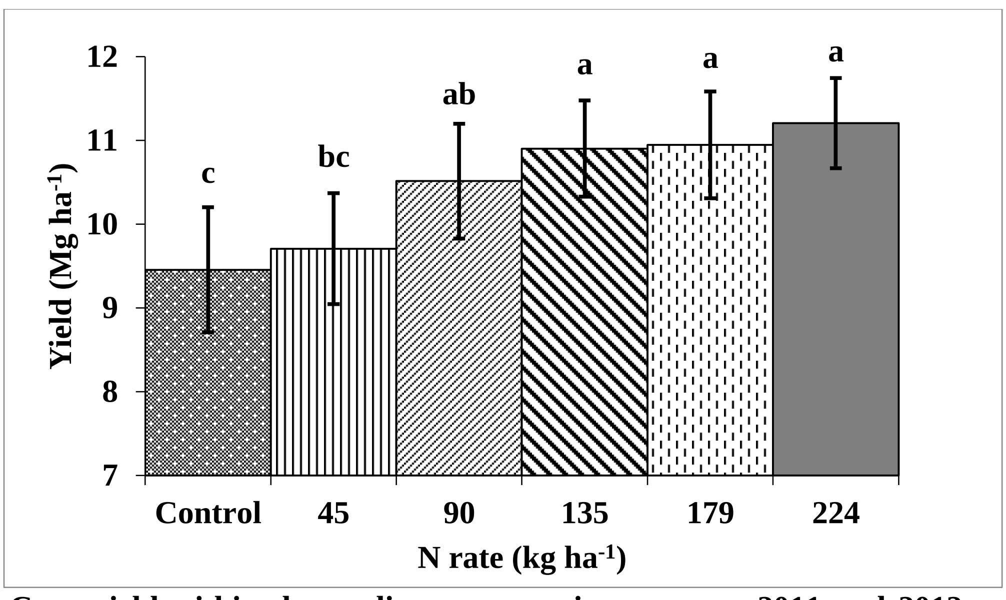

Fig. 3. Corn yield within the medium texture site category, 2011 and 2012 combined, in response to N fertilizer rates. Shaded bars indicate corn yield. Bars with similar letters imposed above are not significantly different from each other at *P* < 0.05.

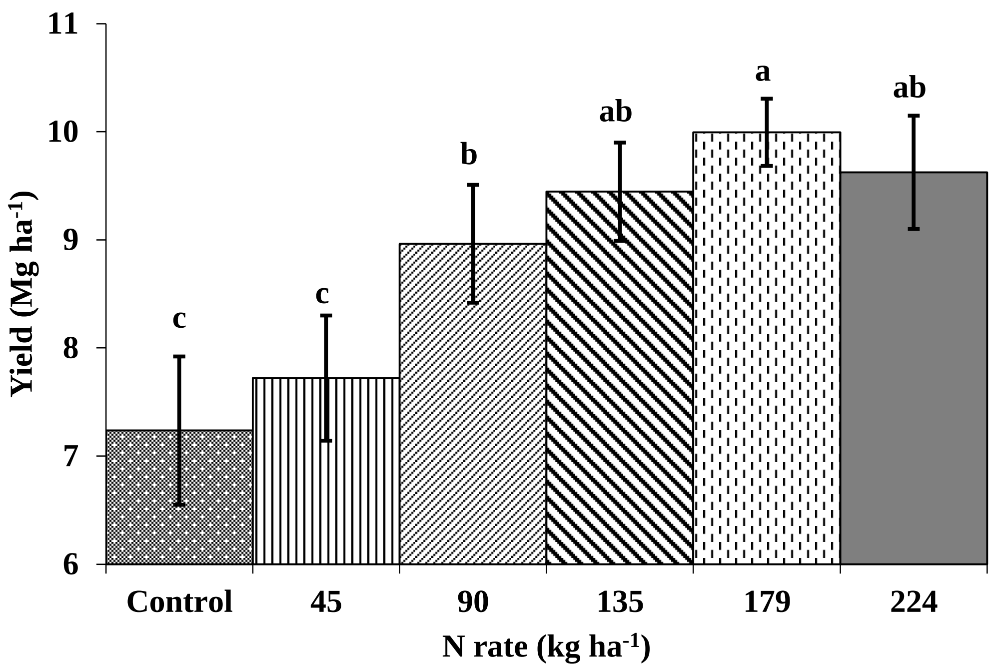

Fig. 4. Corn yield of all eastern no-till category sites, 2011 and 2012 combined, in response to N fertilizer rates. Shaded bars indicate corn yield. Bars with similar letters imposed above are not significantly different from each other at *P* < 0.05.

Table 9. Relationship (r^2) of INSEY (in-season estimate of yield) using the GreenSeeker® sensor and the Holland Crop Circle® sensors at V6 and V12 growth stages with corn yield in eastern medium-textured under conventional tillage in 2011 and 2012. Regression model compared was exponential.

		2011 INSEY†		2012 INSEY†		2011 & 2012 INSEY†	
Growth stage	**Sensor**	**r^2**	**Sig††**	**r^2**	**Sig††**	**r^2**	**Sig††**
V6	GS red NDVI	0.49	***	0.46	***	0.53	***
	CC red-edge NDVI	0.65	***	0.51	***	0.63	***
	CC red NDVI	0.61	***	0.55	***	0.63	***
V12	GS red NDVI	0.17	*	0.12	*	0.13	**
	CC red-edge NDVI	0.35	***	0.33	***	0.36	***
	CC red NDVI	0.10	NS	0.35	***	0.24	***

† INSEY is the sensor reading divided by growing degree days from planting date.
††* denotes significance at 0.001; ** denotes significance at 0.01; * denotes significance at 0.05**

Table 10. Relationship (r^2) of INSEY (in-season estimate of yield) using the GreenSeeker® sensor and the Holland Crop Circle® sensors at V6 and V12 growth stages with corn yield in eastern no-till sites in 2011 and 2012. The model used is exponential.

		2011 INSEY†		2012 INSEY†	
Growth stage	**Sensor type**	**r^2**	**Sig††**	**r^2**	**Sig††**
V6	GS red NDVI	0.05	NS	0.08	NS
	CC red-edge NDVI	0.18	NS	0.33	NS
	CC red NDVI	0.08	NS	0.36	*
V12	GS red NDVI	0.68	***	0.02	NS
	CC red-edge NDVI	0.80	***	0.01	NS
	CC red NDVI	0.62	***	0.01	NS

† INSEY is the sensor reading divided by growing degree days from planting date.
†† * denotes significance at 0.001; * denotes significance at 0.05**

Table 11. Relationship (r2) of INSEY (in-season estimate of yield) using the GreenSeeker® (GS) sensor and the Holland Crop Circle® (CC) sensor at V6 and V12 growth stages with corn yield in the eastern high clay conventional-till sites category in 2011 and 2012. Regression model displayed is exponential.

		2011 INSEY†		2012 INSEY†		2011 & 2012 INSEY†	
Growth stage	**Sensor type**	**r^2**	**Sig††**	**r^2**	**Sig††**	**r^2**	**Sig††**
V6	GS red NDVI	0.40	***	0.60	***	0.53	***
	CC red-edge NDVI	0.01	NS	0.82	***	0.40	***
	CC red NDVI	0.06	NS	0.80	***	0.48	***
V12	GS red NDVI	0.55	***	0.57	***	0.59	***
	CC red-edge NDVI	0.73	***	0.73	***	0.69	***
	CC red NDVI	0.59	***	0.66	***	0.70	***

† INSEY is the sensor reading divided by growing degree days from planting date.
†† * denotes significance at 0.001**

Table 12. Relationship (r2) of INSEY (in-season estimate of yield) using the GreenSeeker® (GS) sensor and the Holland Crop Circle® (CC) sensor at V6 and V12 growth stages with corn yield at all sites in 2011 and 2012. Regression model is exponential.

		2011 INSEY†		2012 INSEY†		2011 & 2012 INSEY†	
Growth stage	**Sensor**	**r^2**	**Sig††**	**r^2**	**Sig**	**r^2**	**Sig**
V6	GS	0.20	***	0.26	***	0.25	***
	CC RE/NIR	0.15	***	0.51	***	0.40	***
	CC R/NIR	0.15	***	0.49	***	0.34	***
V12	GS	0.31	***	0.21	***	0.26	***
	CC RE/NIR	0.47	***	0.25	***	0.46	***
	CC R/NIR	0.29	***	0.19	***	0.27	***

† INSEY is the sensor reading divided by growing degree days from planting date. †† * denotes significance at 0.001; ** denotes significance at 0.01; * denotes significance at 0.05**

5.5. Discussion

The difference in red NDVI and red-edge NDVI INSEY relationship with yield suggests that each wavelength is related to a different plant attribute. The algorithm developed by Kitchen (2006) used two different wavelength ranges. The use of red-edge NDVI is related to plant greenness and not biomass as is red NDVI. The values of red NDVI, red-edge NDVI and INSEY increased with corn maturity. Similar results have been observed by Martin et al. (2007; Raun et al. (2005); Solari et al. (2008). Several studies have suggested that early corn growth stages, V6-V10, are important for sensing in corn (Raun et al., 2005; Kitchen 2006) due to the necessity to amend deficiencies early in the growing season, however, relationships of INSEY and yield tended to improve with sensor readings closer to V10 than with V6. However, as corn maturity advances, the leaves more completely cover the row, resulting in red NDVI readings commonly greater than 0.9, producing a condition called 'saturation'. It is difficult to discriminate differences in plant health or yield prediction when readings are saturated (Townshend et al., 1991). Both the GS and the CC red NDVI provided similar INSEY relationships at V6. However, the CC red-edge NDVI was generally superior to the CC red NDVI and the GS due to saturation of the red-based sensors at V12.

The difference in INSEY and yield relationships between the eastern high clay conventional-till sites and the medium texture sites is probably due to the early season soil wetness in 2011. Total amount of rainfall recorded between April 1 and July 1 during 2011 was about 10 cm greater than normal (NDAWN-North Dakota Agricultural Weather Network- records, http://ndawn.ndsu.nodak.edu/). Consequently, most of the eastern high clay conventional-till sites were water saturated for about 6 weeks, which probably resulted in very high early season denitrification (Sogbedji et al., 2001; van Es et al., 2007). The eastern medium-textured coventional-till sites have the tendency to dry between the rain events due to their better internal drainage, thereby reducing N losses compared to the eastern high clay conventional-till sites.

Sensing was conducted at V6 and V12 stages. There was almost 12-14 day interval between the two growth stages, which is time for factors that might influence the N response and general plant health to affect the relationship between the INSEY with yield at V12 compared to V6 readings. Two different years might be expected to have different soil mineralization potentials. The growing season of 2012 was one of the driest seasons recorded in eastern North Dakota, starting in July 2011 and continuing through August 2012. In spite of the dry season, corn yields were relatively high at most sites in both years (yield ranges in 2011 were 6200 kg ha^{-1} to 13,800 kg ha^{-1}; 2012 yield ranges in 2012 from 6200 kg ha^{-1} to 15,000 kg ha^{-1}, data not shown). According to the Nicolas et al. (2012), the variations in the accumulation of GDD's and the amount and timing of rainfall may have influence on the N response of corn, which could have affected the INSEY and yield relationships between sensor timings and years.

5.6. Conclusion

The CC performed better than GS due to the option of using red-edge NDVI, which outperformed than other two red NDVI options both from CC and GS. The relationship between INSEY and yield at V6 stage was significant for both the GS and CC Red NDVI and CC Red-edge NDVI in the eastern medium-textured coventional-till sites soil category under conventional tillage. The relationship between INSEY and yield under eastern medium-textured coventional-till sites was higher with the CC red-edge NDVI as compared to GS and CC red NDVI at V12. In the eastern no-till sites site category, the INSEY to yield relationship for both sensors was significant at the V12 stage in 2011, but not in 2012, because the relationship between years was very different in 2011 compared to 2012, a combined analysis was not conducted. The lack of INSEY relationship to yield in 2011 and 2012 at the V6 stage might be explained by slow early corn growth in each year under eastern no-till sites compared to the conventional tillage sites. At V12 in 2011, the prediction of yield was improved, probably because the earlier detrimental effects of residue cover were diminished with time and soil warming.

5.7. Literature Cited

Aparicio, N., D. Villegas, J. L. Araus, J. Casadesus, and C. Royo. 2002. Relationship between growth traits and spectral vegetation indices in durum wheat. Crop Sci. 42:1547–1555.

Araus, J. L. 1996. Integrative physiological criteria associated with yield potential. In: Reynolds MP, Rajaram S, McNab A, editors. Increasing yield potential in wheat: breaking the barriers. Mexico, DF: CIMMYT; pp. 150–167.

Bausch, W.C., and H.R. Duke.1996. Remote sensing of plant nitrogen status in corn. T. Am. Soc. Agric. Eng. 39:1869-1875.

Blackmer, A.M., R. D.Voss, and A. P. Mallarino, 1997. Nitrogen fertilizer recommendations for corn in Iowa. Pm-1714. Iowa State Univ., Ames, IA.

Blackmer, T.M., J.S. Schepers, G.E. Varvel, and E.A. Walter-Shea. 1996a. Nitrogen deficiency detection using reflected shortwave radiation from irrigated corn canopies. Agron. J. 88: 1-5.

CAST. 1999. Gulf of Mexico hypoxia: Land and sea interactions. Task Force Report No. 134. Council for Agricultural Science and Technology, Ames, IA.

Evans, L.T., and R.A. Fischer. 1999. Yield potential: Its definition, measurement, and significance. Crop Sci. 39:1544-1551.

Franzen, D. W. 2010. North Dakota fertilizer recommendation tables and equations. NDSU Extension Circular SF-882. North Dakota State University Extension Service, Fargo, ND.

Franzen, M. 2012. Program for initial analysis of Greenseeker and Holland Crop Circle Sensor raw data within Excel. Unpublished program. Fargo, ND.

Freeman, K.W., D.B. Arnall, R.W. Mullen, K. Girma, K.L. Martin, R.K. Teal, and W.R. Raun. 2007. By-plant prediction of corn forage biomass and nitrogen uptake at various stages using remote sensing and plant height measures. Agron. J. 99: 530-536.

IDRE-USDA, 2013. SAS FAQ: How do I compare regression coefficients between two groups? http://www.ats.ucla.edu/stat/sas/faq/compreg2.htm .

Inman, D., R. Khosla, D. G. Westfall, and R. Reich, 2005. Nitrogen uptake across site specific management zones in irrigated corn production systems. Agron. J. 97: 169-176.

Inman, D., R. Khosla, R. Reich, and D. Westfall. 2007. Active remote sensing and grain yield in irrigated maize. Precis. Agric. 8:241-252.

Jordan, C.F. 1969. Derivation of leaf area index from quality of light on the forest floor. Ecology 50: 663-666.

Kitchen, N. 2006. Variable-rate nitrogen fertilizer application in corn using in-field sensing of leaves or canopy. Agronomy technical note MO-35. Columbia, MO: USDA.

Lillesand, T.M., and R.W. Kiefer. 1994. Remote sensing and photo interpretation. 3rd ed. John Wiley & Sons, New York. 750 p.

Martin, K.L., K. Girma, K.W. Freeman, R.K. Teal, B. Tubańa, D.B. Arnall, B. Chung, O. Walsh, J.B. Solie, M.L. Stone, and W.R. Raun. 2007. Expression of variability in corn as influenced by growth stage using optical sensor measurements. Agron. J. 99: 384-389.

Nicolas T., Y. M. Bouroubi, C. Bélec, R. W. Mullen, N. R. Kitchen, W. E. Thomason, S. Ebelhar, D. B. Mengel, W. R. Raun, D. D. Francis, E. D. Vories, and I. Ortiz- Monasterio. 2012.

Corn response to nitrogen is influenced by soil texture and weather. Agron. J. 104: 1658–1671.

Olsen, S. R., C.V. Cole, F. S. Watanabe, and L. A. Dean. 1954. Estimation of available phosphorus in soils by extraction w ith sodium bicarbonate. USDA Circular 939. U.S. Government Printing Office, Washington D.C.

Osborne, S.L., J.S. Schepers, D.D. Francis, and M.R. Schlemmer. 2002. Use of spectral radiance to estimate In-Season biomass and grain yield in nitrogen and water stressed corn. Crop Sci. 42:165-171.

Penny, D.C. 1996. Yield and nutrient mapping for site-specific fertilizer management. Commun. Soil. Sci. Plant Anal. 27: 1265-1279

Penuelas, J., J.A. Gamon, A.L. Fredenn, J. Merino, and C.B. Field. 1994. Reflectance indices associated with physiological changes in nitrogen and water-limited sunflower leaves. Remote Sens. Environ. 48: 135-146.

Penuelas, J., and I. Filella. 1998. Visible and near-infrared reflectance techniques for diagnosing plant physiological status. Trends in Plant Sci. 3: 151-156.

Raun, W. R. and G. V. Johnson. 1999. Improving Nitrogen Use efficiency for cereal production. Agron. J. 91: 357-363.

Raun, W.R., J. B. Solie, G. V. Johnson, M. L. Stone, R. W. Mullen, K.W. Freeman, W. E. Thomason, and E. V. Lukina. 2002. Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. Agron. J. 94: 815-351.

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

Rouse, J. W. Jr., R. H. Haas, J. A. Schell, and D. W. Deering. 1973. Monitoring vegetation systems in the Great Plains with ERTS. In: S. C. Freden, E. P. Mercanti, & M. A. Becker (Eds.), *Third ERTS Symposium* (Vol. 1, pp. 309–317). NASA, Washington, DC, USA: NASA Special Publication SP-351.

Schilling, K.E. 2002. Chemical transport from paired agricultural and restored prairie watersheds. J. Environ. Qual. 31: 1184-1193.

Schulte, E. E., and B. G. Hopkins. 1996. Estimation of soil organic matter by weight-loss-on ignition. Chap. 3. In: F. R. Magdoff et al. (ed.). Soil Organic Matter: Analysis and Interpretation. SSSA Spec. Publ. 46, SSSA, Madison, Wis.

Shanahan, J.F., J. S. Schepers, D. D. Francis, G. E. Varvel, W. W. Wilhelm, J. M. Tringe, M. S. Schlemmer, and D. J. Major. 2001. Use of remote sensing imagery to estimate corn grain yield. Agron. J. 93: 583-589.

Sogbedji, J. M., H. M. van Es, S. D. Klausner, D. R. Bouldin, and W. J. Cox. 2001. Spatial and temporal processes aff ecting nitrogen availability at the landscape scale. Soil Tillage Res. 58: 233–244.

Solari, F., J. F. Shanahan, R. B. Ferguson, J. Schepers, J., and A. Gitelson. 2008. Active sensor reflectance measurements of corn nitrogen status and yield potential. Agron. J. 100: 571-579.

USDA-NASS. 2003. http://www.ers.usda.gov/Data/FertilizerUse/

Steinheimer, T. R., K. D. Scoggin, and L. A. Kramer. 1998. Agricultural chemical movement through a field size watershed in Iowa: Surface hydrology and nitrate losses in discharge. Environ. Sci. Technol. 32:1048-1052.

Stone, M. L., J. B. Solie, W. R.Raun, R. W. Whitney, S. L. Taylor, and J. D. Ringer. 1996. Use of spectral radiance for correcting in season fertilizer nitrogen deficiencies in winter wheat. T. Am. Soc. Agric. Eng. 39: 1623-1631.

Teal, R.K., B. Tubana, K. Girma, K.W. Freeman, D.B. Arnall, O. Walsh, and W.R. Raun. 2006. In-season prediction of corn yield potential using NDVI at various vegetative growth stages. Agron. J. 98: 1488-1494.

Townshend, J., C. Justice, W. Li, C. Gurney, and J. McManus. 1991. Global land cover classification by remote sensing: present capabilities and future possibilities. Remote Sens. Environ. 35: 243-255.

van Es, H.M., C. L. Yang, and L. D. Geohring. 2005. Maize nitrogen response as affected by soil type and drainage variability. Precis. Agric. 6:281–295.

Watson, D., and J. R. Brown. 1998. pH and lime requirement. In Brown, J. R. (ed.) Recommended Chemical Soil Test Procedure for the North Central Region. North Central Regional Res. Pub. No. 221 (revised). Missouri Agric. Exp. Stat. SB 1001, Univ. of Missouri, Columbia, p. 13.

Wibawa, W. D., D. L. Dludlu, L. J. Swenson, D. G. Hopkins, and W. C. Dahnke. 1993. Variable fertilizer application based on yield goal, soil fertility, and soil map unit. J. Prod. Agric. 6: 255–261.

CHAPTER VI. ALGORITHMS FOR USE IN DIRECTING IN-SEASON NITROGEN RATES FOR CORN

6.1. Abstract

Forty-six sites in southeastern and west-river North Dakota were used to conduct N rate trials on field corn in 2011, 2012, and 2013. All locations were categorized as eastern high clay (soil survey description) conventional-till sites and eastern medium-textured conventional-till sites (soil survey description) soil types as well as long-term eastern no-till sites and west-river sites with further division into higher and lower yielding eastern high clay conventional-till sites and eastern medium-textured coventional-till sites. Two ground based active-optical sensors, the GS and CC were used to collect red NDVI or red-edge NDVI data in each plot at the V6 and V12 growth stages. Significant relationships between both sensor readings at both growth stages using red NDVI and red-edge NDVI were found in all soil and tillage systems except lower yield medium texture sites, which were probably affected by large nitrate leaching losses in some years.

Key Words: Canopy sensor, NDVI, nitrogen

6.2. Introduction

For the past sixty years, increasing food production has been a global priority of agriculture (Johnston 2000). During this time, supplemental application of nitrogen (N) as a fertilizer increased more than other nutrients because of its direct impact on greater crop yield over most agricultural land. Nitrogen use efficiency (NUE) by crops is estimated to be 33% of the amount applied (Raun and Johnson, 1999). Nitrogen use efficiency is a metric relating crop N uptake to the quantity of N applied. The NUE is defined as the mass of grain harvested compared to the mass of N applied. Because there is considerable yield variability and variability of potential N loss variability within fields developing fertilization practices that optimize N fertilizer rates in-season has the potential to enhance grower profitability and NUE.

Extensive use of N fertilizer and its low NUE due to its transormations (nitrate, nitrite, ammonium, ammonia, and nitrous oxide) within the soil has resulted in degradation of some ecosystems because of surface and groundwater nitrate contamination from leaching or runoff, and increased N_2O from denitrification (Steinheimer et al., 1998). Current N management practices in the Corn Belt region of the USA are partially responsible for the nitrates found in ground and surface water (Schilling, 2002; Steinheimer et al., 1998; CAST 1999). The nitrate concentration in Mississippi River water flowing into the Gulf of Mexico may have contributed to the hypoxia in this region (Rabalais, 2002; Turner and Rabalais, 1991).

The low NUE of present N management practices is partly due to poor synchrony between N application and crop demand (Fageria and Baligar, 2005; Cassman et al., 2002; Raun and Johnson, 1999). The time between N application and its active uptake by the crop provides opportunities for N loss through leaching, clay fixation, immobilization, denitrification, and volatilization (Cassman et al., 2002). Over the past 20 years, average N application in the Corn Belt was approximately 150 kg ha^{-1} (USDA statistics, 2003) with 75% of the applications made prior to planting and 25% after planting (Cassman et al., 2002).

Soil and plant analysis is being used for N management in different crops (Schroder et al., 2000). Some states include soil organic matter (Nebraska, North Dakota, Missouri and Minnesota), nitrate-nitrogen credit from the previous crop (Nebraska, Illinois, Iowa, North Dakota, South Dakota and Minnesota), yield goal (Nebraska, South Dakota and North Dakota), and N credit from nitrogen from manures and irrigation water (Dobermann and Cassman, 2002). Yield goal or yield potential are used within the N rate formula in some states (Nebraska, South Dakota and North

Dakota) N credits from manure (all states) (Dobermann and Cassman, 2002) and irrigation water nitrate (Dobermann and Cassman, 2002) are also used to formulate N rates. To supply the required amount of N with consideration of spatial variability, some studies (Franzen et al., 2002; Ferguson et al., 2003) have encouraged a soil-based approach of delineating management zones (MZ). Because of the temporal variation of soil nitrate (Jaynes and Colvin, 1997; Ferguson et al., 2002; Eghball et al., 2003; Dobermann et al., 2003; Schepers et al. 2004; Lambert et al., 2006), there has been some reluctance in southern states to use preplant nitrate analysis such as Arkanasa, Georgia, and Louisiana. In these states, studies have indicated that MZ's alone might not be adequate to account for all of the variability of N requirement in a field.

The yield potential or yield goal strategy as a basis for N fertilization has been used for over forty years in the USA (Raun et al., 2001). The recommended N rate for corn in North Dakota is currently determined by a formula that includes yield potential, soil test nitrate analysis before planting to 60-cm in depth, and any N credits from previous crops (Franzen, 2006). One method of defining the target yield is to average crop yield over the five to seven most recent years, then add a margin of 'insurance' of five to ten percent (Rice and Havlin, 1994). However, surveys have reported that most of the producers overestimate the target yield to develop their N requirement beyond a ten percent insurance margin (Goos and Prunty, 1990; Schepers and Mosier, 1991). In some years, the low cost of N fertilizer encourages producers to over-apply N so it will not be a limiting factor for yield.

The approach of in-season N recommendation using a sensor based algorithm has been successfully used in corn (Biermacher et al. 2006; Ortiz-Monasterio and Raun 2007; Raun et al. 2001; Teal et al. 2006). A strategy for implementing in-season N application is based on the use of ground-based active-optical (GBAO) sensors such as the GS and CC. The GBAO sensors can be used at any pre-flowering growth stage of crop without consideration of clouds and ambient light. The GBAO sensors emit specific light-spectrum wavelengths related to crop biomass or leaf chlorophyll in a. The GBAO sensors emit the light in series of pulses of predetermined light and no light time duration in a specific code. The sensors on the GBAO read only the light received in the coded modulation, resulting in filtering out any radiation from non-GBAO source.

The GS algorithm for corn (Raun et al. 2005) uses the 'in-season estimate of yield' (INSEY) as a normalization method to allow for sensing at different growth stages in the immediate neighborhood of stages surrounding the growth stage of the algorithm. The INSEY is a ratio of NDVI readings from GS divided by growing degree days from the date of planting. This method can also be applied to the CC sensor, although using a ratio defined as the sufficiency index (SI) has been recommended by Holland and Schepers (2010). The SI is the yield at the sensor reading from an N non-limiting area divided by yield from an N limiting area. Although, some features of the two approaches are essentially the same for example the RI and SI features are essentially each other's inverse and therefore both seek to estimate the difference between an N-limiting crop and a non-N-limiting crop but they differes from each other in predicting the n requirement.

The Oklahoma State University approach is a mass balance approach. The weakness of this approach is that it may be limited in application to the area in which it is developed. Regional factors must be known, such as the maximum yield potential for the geographic area. Additionally, it is sensitive to environmental impacts. For example, detrimental weather events (wind, hail, drought, etc.) after the time of crop sensing and in-season N application will likely drastically change the anticipated yield. This will almost certainly reduce the efficiency of the N application that was applied as the N recommendation is fundamentally based on the estimated yield. Because of this, it would appear the algorithm is more likely to result in over-application of N (due to previously mentioned weather factors) than under-application of N. This may be a strength of the approach, because as long as estimated yield values are high enough, yield should not be limited due to N. The University of Nebraska-Lincoln approach is based on known relationships between certain measurements (for example, between SI and N rate, and between N uptake and growth stage). Because of this, the model should be more applicable across many regions. A limitation is that users require estimation of the optimum N rate. Additionally, the optimum N rate varies drastically from year to year and therefore it is impossible for a producer to anticipate what the true optimum N rate would be at planting, or mid-season. Furthermore, in cases where large amounts of early-season N loss occur, the algorithm may under-estimate N requirements.

The objective of this study was to develop algorithms using the GS and CC Sensor® for in-season corn N rate prediction estimation under dryland conditions with different soil textures, relative soil productivities and cultivation practices.

6.3. Material and Methods

6.3.1. Locations

Forty-six sites were used for N rate trials on field corn in North Dakota in 2011, 2012, and 2013 (Table 13). Permission was granted by farmer cooperators for the establishment of experimental sites within their larger farm fields. Farmer cooperators included growers with whom NDSU researchers had worked with in the past, farmers recommended by county Extension agents and farmers who volunteered after presentations at winter meetings. No supplemental N was applied to any experimental site by the cooperator, except small amounts included in a low rate at planting banded starter application. The cooperators planted a corn hybrid of their choice at each site and the growers applied herbicides at their discretion. Hand weeding was completed as needed.

The experimental design was a randomized complete block with four replications and six N treatments as ammonium nitrate broadcast by hand within one week of planting: check (no added N), 45, 90, 134, 179 and 224 kg N ha^{-1}. Each experimental unit (plot) was 6.1-m in length and 3.05-m in width. Locations were categorized into eastern high clay conventional-till sites and eastern medium-textured conventional-till sites types as well as long-term eastern and west-river sites. Eastern high clay conventional-till sites and eastern medium-textured coventional-till sites were further divided into higher and lower yielding sites, with 10 Mg ha^{-1} corn grain as the yield division criteria between higher and lower. Soil textures at eastern high clay conventional-till sites were silty clay loam or higher clay, whereas eastern medium-textured coventional-till sites were fine sandy loams, silt loam, loam, and sandy loam textures. Long-term eastern and west-river sites were continuous no-till for at least six years. Categorization was the result of using a multiple regression analysis to determine if N response was related to any of the suspected categories above.

One NDSU experimental site was selected at Casselton seed farms to demonstrate the N rate study to North Dakota growers during field days and educational tours. The site was planted and maintained according to the NDSU Extension recommendations.

6.3.2. Soil sampling

From each site, five soil sample cores were taken before starting of field work using a 2.5-cm diameter hand probe to a depth of 0-15 cm for phosphorous (P), potassium (K), zinc (Zn), pH, and organic matter analysis. Three soil cores from 0-60 cm were obtained for residual nitrate. Cooperators did not apply any K or P to the sites. Fertilizer P and K were applied as mono ammonium phosphate (11-52-0) and potassium chloride (0-0-60), respectively, at rates recommended within North Dakota Extension guidelines (Franzen, 2010). If the site was found deficient in Zn, zinc sulfate (36% granules) at a rate of 11 kg ha^{-1} was applied by hand as a broadcast at the time of treatment application. If the site was suspected to be S deficient before planting due to sandy texture and high rainfall/snowmelt, 112 kg ha^{-1} of calcium sulfate (0-0-0-20S) was applied at the time of N application. In the sites where S deficiency appeared at V6, an application of calcium sulfate at 22 kg ha^{-1} S (112 kg ha^{-1} gypsum) was applied as granules over the top of the corn. Soil pH was analyzed using a 1:1 soil: deionized H_2O solution method (Watson and Brown, 1998); P was determined by the Olsen method (Olsen et al., 1954b), K was assessed using the 1-N ammonium acetate method (Thomas, 1982). The DTPA extraction method (Lindsay and Norvell, 1978) coupled with atomic absorption spectroscopy detection was used for determination of available Zn. Organic matter was measured using the loss following ignition method (Schulte and Hopkins, 1996).

6.3.3. Sensing procedure

The readings from both GS and CC_ ACS-470 were obtained at the V6 stage and again about 10 days to 2 weeks later at the V12 stage. Sensor readings were obtained over the top of the corn whirls from the middle row of each plot. All reflectance data (NDVI) were inserted within the generalized expression from eq. 1:

NDVI= (NIR – red or red-edge) / (NIR+ red or red-edge)

The wavelength measurement from the red-edge differs from the red NDVI measurement because the red-edge measures the plant chlorophyll content (Horler et al., 1983). The mean of GS and CC Sensor® readings was obtained from 30 and 50 individual readings within each plot. The mean values within a treatment were calculated using in-house macro programs for Gs and CC Sensor® raw data developed using Visual Basic within Excel (Franzen 2012). The INSEY was calculated by dividing the sensor reading with the growing degree days, NDAWN data (http://ndawn.ndsu.nodak.edu), from the date of planting to sensing.

Table 13. GPS coordinates and soil series for field experiments in 2011 through 2013.

Year	Locations	GPS coordinates	Soil Series†
2011	Valley City	46° 52' 49.090" N, 97° 54' 46.240" W	Fine-loamy, mixed, superactive, frigid Calcic Hapludolls
	Rutland	45° 59' 58.051" N, 97° 28' 43.634" W	Fine-loamy, mixed, superactive, frigid Pachic Argiudolls
	Havana	45° 56' 04.266" N, 97° 35' 54.633" W	Fine-silty, mixed, superactive, frigid Pachic Hapludolls
	Durbin	46° 51' 29.495" N, 97° 09' 26.907" W	Fine, smectitic, frigid Typic Epiaquerts
	Mooreton	46° 12' 40.420" N, 96° 46' 43.259" W	Fine, smectitic, frigid Typic Epiaquerts
	Great Bend	46° 07' 54.977" N, 96° 43' 11.481" W	Fine, smectitic, frigid Typic Natraquerts
	Fairmount	45° 59' 39.021" N, 96° 35' 46.219" W	Fine-loamy, mixed, superactive, frigid Aeric Calciaquolls
	Christine	46° 53' 30.423" N, 96° 54' 05.749" W	Fine, smectitic, frigid Typic Epiaquerts
	Prosper	46° 56' 55.978" N, 97° 02' 48.344" W	Fine, smectitic, frigid Typic Calciaquerts
	Milnor	46° 16' 34.108" N, 97° 28' 02.389" W	Sandy, mixed, frigid Oxyaquic Hapludolls
	Page 2	47° 09' 36.755" N, 97° 25' 48.088" W	Fine-loamy, mixed, superactive, frigid Calcic Hapludolls
	Buffalo	46° 56' 51.974" N, 97° 28' 01.950" W	Fine-loamy, mixed, superactive, frigid Calcic Hapludolls
	Page 1	47° 09' 05.282" N, 97° 23' 21.552" W	Coarse-loamy, mixed, superactive, frigid Pachic Hapludolls
	Walcott	46° 30' 02.183" N, 97° 02' 32.182" W	Coarse-loamy, mixed, superactive, frigid Aquic Pachic Hapludolls
	Arthur	47° 03' 43.560" N, 97° 08' 04.248" W	Coarse-silty, mixed, superactive, frigid Aeric Calciaquolls
2012	Rutland East	45° 59' 36.599" N, 97° 27' 28.969" W	Fine-loamy, mixed, superactive, frigid Pachic Argiudolls
	Rutland West	45° 59' 32.671" N, 97° 30' 15.115" W	Fine-silty, mixed, superactive, frigid Aeric Calciaquolls
	Leonard-North	46° 42' 04.081" N, 97° 16' 52.371" W	Fine-silty, mixed, superactive, frigid Aeric Calciaquolls
	Casselton North	46º56’ 12.417” N, 97º 17’ 00.351”W	Fine-silty, mixed, superactive, frigid Aeric Calciaquolls
	Amenia	47° 00' 13.913" N, 97° 12' 57.025" W	Coarse-silty, mixed, superactive, frigid Aeric Calciaquolls
	Casselton South	46° 56' 26.922" N, 97° 17' 00.351" W	Fine, smectitic, frigid Typic Epiaquerts
	Galchutt	46° 23' 00.519" N, 96° 43' 48.576" W	Fine, smectitic, frigid Typic Natraquerts
	Fairmount North	45° 59' 38.268" N, 96° 38' 18.155" W	Coarse-silty, mixed, superactive, frigid Aeric Calciaquolls
	Fairmount South	45° 57' 23.964" N, 96° 34' 35.244" W	Fine-loamy, mixed, superactive, frigid Aeric Calciaquolls
	Great Bend	46° 08' 20.469" N, 96° 44' 09.026" W	Fine, smectitic, frigid Typic Natraquerts
	Prosper	46° 58' 10.307" N, 96° 59' 20.466" W	Fine, smectitic, frigid Typic Epiaquerts

(continues)

Table 13. GPS coordinates and soil series for field experiments in 2011 through 2013 (continued)

Year	Locations	GPS coordinates	Soil Series†
2012	Barney	46° 10' 58.074" N, 96° 55' 43.331" W	Fine, smectitic, frigid Typic Epiaquerts
	Mooreton	46° 18' 13.407" N, 96° 51' 40.672" W	Coarse-loamy, mixed, superactive, frigid Aeric Calciaquolls
	Gardner	47° 09' 57.820" N, 97° 02' 59.152" W	Fine, smectitic, frigid Vertic Argialbolls
	Arthur	47° 06' 25.800" N, 97° 14' 36.562" W	Fine, smectitic, frigid Vertic Argialbolls
	Wheatland	46° 55' 06.854" N, 97° 23' 14.391" W	Fine-loamy, mixed, superactive, frigid Aeric Calciaquolls
	Milnor	46° 13' 11.317" N, 97° 25' 31.110" W	Fine-loamy, mixed, superactive, frigid Pachic Argiudolls
	Leonard South	46° 40' 32.061" N, 97° 17' 02.579" W	Sandy, mixed, frigid Typic Endoaquolls
	Walcott west	46° 30' 29.560" N, 97° 03' 00.760" W	Coarse-loamy, mixed, superactive, frigid Aeric Calciaquolls
	Walcott east	46° 29' 44.107" N, 96° 53' 04.456" W	Coarse-silty over clayey, mixed over smectitic, superactive, frigid Aeric Calciaquolls
2013	Casselton	46º 52’ 41.973” N, 97º 14’ 55.894” W	Fine-silty, mixed, superactive, frigid Typic Endoaquolls
	Durbin	46º 51’ 22.072” N, 97º 09’ 28.366” W	Fine, smectitic, frigid Typic Epiaquerts
	Barney	46º 15’ 07.560” N, 96º 59’ 28.627” W	Coarse-loamy, mixed, superactive, frigid Aquic Pachic Hapludolls
	Dwight	46º 18’ 39.335” N, 96º 47’ 12.237” W	Fine, smectitic, frigid Vertic Argialbolls
	Gardner	47º 10’ 28.482” N, 96º 54’ 02.138” W	Fine, smectitic, frigid Typic Epiaquerts
	Leonard-North	46º 52’ 57.807” N, 97º 17’ 44.945” W	Fine, smectitic, frigid Typic Epiaquerts
	Walcott	46º 30’ 02.359” N, 97º 02’ 39.660” W	Coarse-loamy, mixed, superactive, frigid Aeric Calciaquolls
	Leonard West	46º 39’ 10.750” N, 97º 18’ 12.980” W	Coarse-loamy, mixed, superactive, frigid Pachic Hapludolls
	Arthur	47º 06’ 50.963” N, 97º 57’ 55.219” W	Coarse-silty, mixed, superactive, frigid Pachic Hapludolls
	Rutland	45º 57’ 50.176” N, 97º 31’ 44.205” W	Fine, smectitic, frigid Pachic Vertic Argiudolls
	Jamestown	46º 45’ 58.571” N, 98º 47’ 55.930” W	Fine-loamy, mixed, superactive, frigid Calcic Hapludolls
	Mott	46° 56' 43.583" N, -102° 19' 10.919" W	Fine-loamy, mixed, superactive, frigid Typic Haplustolls
	Richardton	46° 35' 0.095" N, -102° 21' 41.364" W	Fine-loamy, mixed, superactive, frigid Typic Haplustolls
	Beach	46° 49' 3.0354" N, -103° 59' 40.451" W	Fine-silty, mixed, superactive, frigid Typic Haplustolls
	New Leipzig	46° 26' 44.051" N, -101° 56' 31.379" W	Fine, smectitic, frigid Vertic Natrustolls

† information collected from Soil Survey Staff, 2013.

Table 14. Tillage system, planting date and date of the first and second sensing of each location, 2011, 2012, and 2013.

Year	Locations	Tillage/Soil Type	Planting Date	1st Sensing	2nd Sensing	Corn Variety†
2011	Valley City	Eastern no-till sites	05/10/11	06/24/11	07/14/11	Pannar-409
	Rutland	Eastern no-till sites-Eastern	05/19/11	06/30/11	07/14/11	DK 43-30
	Havana	Eastern no-till sites-Eastern	05/17/11	06/30/11	07/14/11	38A56
	Durbin	Eastern high clay conventional-till sites	05/08/11	06/20/11	07/13/11	DeKalb-4492
	Mooreton	Eastern high clay conventional-till sites	05/17/11	07/01/11	07/13/11	Pioneer 38M58
	Great Bend	Eastern high clay conventional-till sites	05/13/11	06/20/11	07/13/11	Nk 29T-3000
	Fairmount	Eastern high clay conventional-till sites	06/04/11	07/12/11	07/26/11	Proseed 787
	Christine	Eastern high clay conventional-till sites	05/19/11	07/01/11	07/19/11	Croplan
	Prosper	Eastern high clay conventional-till sites	05/25/11	07/06/11	07/18/11	PFS76F82VT2 Pro
	Milnor	Eastern medium-textured conventional-till sites	05/16/11	06/30/11	07/14/11	Gold County 9429V93
	Page 2	Eastern medium-textured conventional-till sites	05/19/11	07/05/11	07/18/11	wensman 8089
	Buffalo	Eastern medium-textured conventional-till sites	05/18/11	07/06/11	07/18/11	P2046
	Walcott	Eastern medium-textured conventional-till sites	05/18/11	07/01/11	07/19/11	43-30RR
	Arthur	Eastern medium-textured conventional-till sites	05/17/11	07/05/11	07/18/11	Proseed 92RR
2012	Rutland east	Eastern no-till sites	05/17/12	06/11/12	06/25/12	Funks 092
	Rutland west	Eastern no-till sites	05/01/12	06/11/12	06/25/12	Pioneer 38A56
	Leonard-North	Eastern high clay conventional-till sites	04/26/12	06/12/12	06/25/12	Peterson 76R92
	Casselton North	Eastern high clay conventional-till sites	04/22/12	06/12/12	06/25/12	vigaro v23yr82
	Casselton South	Eastern high clay conventional-till sites	04/22/12	06/12/12	06/25/12	Vigaro-v23yr82
	Fairmount West	Eastern high clay conventional-till sites	04/26/12	06/11/12	06/26/12	Proseed 793 GT
	Fairmount south	Eastern high clay conventional-till sites	05/09/12	06/11/12	06/26/12	Pioneer38A57 RR/BT
	Great Bend	Eastern high clay conventional-till sites	05/11/12	06/13/12	06/26/12	Pioneeer38M58
	Prosper	Eastern high clay conventional-till sites	04/24/12	06/12/12	06/25/12	PFS 56I92
	Barney	Eastern high clay conventional-till sites	04/30/12	06/11/12	06/26/12	Mix of DK 4837/4620
	Gardner	Eastern medium-textured conventional-till sites	04/25/12	06/12/12	06/25/12	Pioneer 39V07
	Arthur	Eastern medium-textured conventional-till sites	04/23/12	06/04/12	06/25/12	Mycogen 2g192
	Wheatland	Eastern medium-textured conventional-till sites	04/16/12	06/12/12	06/25/12	NA

(continues)

Table 14. Tillage system, planting date and date of the first and second sensing of each location, 2011, 2012, and 2013 (continued)

Year	Locations	Tillage/Soil Type	Planting Date	1st Sensing	2nd Sensing	Corn Variety†
2012	Milnor	Eastern medium-textured conventional-till sites	04/15/12	06/13/12	06/25/12	Seed2000-9602
	Leonard South	Eastern medium-textured conventional-till sites	04/09/12	06/12/12	06/25/12	Peterson 26I92
	Walcott west	Eastern medium-textured conventional-till sites	04/30/12	06/11/12	06/25/12	P9675 AMX-R
	Walcott east	Eastern medium-textured conventional-till sites	04/26/12	06/13/12	06/25/12	P9519 HR
2013	Casselton	Eastern high clay conventional-till sites	05/15/13	06/25/13	07/15/13	P8640
	Durbin	Eastern high clay conventional-till sites	05/15/13	06/25/13	07/15/13	NA
	Barney	Eastern high clay conventional-till sites	05/09/13	06/26/13	07/18/13	P9917
	Dwight	Eastern high clay conventional-till sites	05/16/13	06/26/13	07/09/13	DK 4837
	Gardner	Eastern high clay conventional-till sites	05/10/13	06/35/13	07/10/13	NutTech3A183
	Leonard-North	Eastern high clay conventional-till sites	05/28/13	06/25/13	07/10/13	76R92
	Walcott	Eastern medium-textured conventional-till sites	05/18/13	07/02/13	07/18/13	DeKalb 39-04
	Leonard West	Eastern medium-textured conventional-till sites	05/10/13	07/02/13	07/12/13	76R92
	Arthur	Eastern medium-textured conventional-till sites	05/15/13	06/20/13	07/10/13	Mycogen-2T222
	Rutland	Eastern no-till sites	05/08/13	06/18/13	07/09/13	Mycogen 2G-161
	Jamestown	Eastern no-till sites	05/11/13	06/18/13	07/09/13	Croplan 229VT2RTB
	Mott	West river sites	05/19/13	07/01/13	07/17/13	P8107
	Richardton	West river sites	05/13/13		07/17/13	P8107
	Beach	West river sites	05/15/13	07/01/13	07/17/13	Pioneer D-97
	New Leipzig	West river sites	05/07/13	07/01/13	07/17/13	P8954XR

† **NA-data not available**

6.3.4. Harvest

After maturity, the sensed row (6.1-m in length) was hand harvested, dried to about 10 per cent moisture and then shelled using an Almaco® corn sheller in 2011. Moisture at shelling was determined on a grain subsample using a Dickey-John® moisture-test weight sensor (Dickey-John, Auburn, IL, USA). In 2012 and 2013, a newer model Almaco corn sheller was used that allowed complete shelling of wet corn, so corn was shelled directly from the field without a need for drying. Moisture was measured on shelled grain using the same sensoras in 2011.

6.3.5. Statistical analysis

Regression analyses were conducted on sensor readings and yield with yield as the dependent variable and INSEY as the independent variable. A preliminary analysis in 2011 was conducted which compared the relationship of yield to INSEY using linear, quadratic, square root, logarithmic, and exponential models. Following this preliminary analysis, exponential relationships described the relationships of INSEY and yield at high frequency as compared to other models. Therefore, exponential models are used. Multiple regression analysis was used to determine whether the data should be segregated into long-term eastern no-tilll and west-river sites, eastern high clay conventional-till sites, and eastern medium-textured coventional-till sites. The analysis confirmed that segregation of the data into those categories improved the relationship between INSEY and yield.

The regression coefficient (r^2) value was used to evaluate the relationship of crop yield and sensor reading at V6 and V12. The SAS procedure for Windows V9.2 (SAS Institute, Cary, NC) was used to calculate the r^2 exponential regression model. SAS GLM was used to compare the N treatments for treatment differences. A P-value of 5% probability was used to differentiate the treatments from each other in terms of statistical differences between treatments.

6.4. Results

The regression coefficient (r^2) and P value for comparing INSEY and yield were similar for four regression models: linear, quadratic, logarithmic, and exponential regression models under each cropping system and soil textures. The exponential regression model was found to most consistently represent relationships. Previous work supports the choice of the exponential regression model to relate INSEY and yield (Raun et al., 2005). Accumulation of biomass during corn growth fits an exponential model until reproductive stage (Vanderlip and Fjell, 1994) which also supports the use of an exponential model. Therefore, the exponential model was used to compare relationships between INSEY and yield (Fig 5 to 40).

The regression coefficient r^2 for the relationship between INSEY and yield was significant for most of the relationships. The red NDVI was a good predictor of yield throughout the study. When the sites were categorized into eastern high clay conventional-till sites and eastern medium-textured coventional-till sites, west-river sites, and eastern long-term no-till sites there were significant improvement in yield and INSEY relationships over a combined site analysis.

Eastern high clay conventional-till sites were categorized into high and low yielding sites due to difference in N response at a dividing yield of 10 and 10±1 Mg ha^{-1} (Fig 5, 6, 7, and 8), respectively. Despite different environmental conditions between sites, the relationship between yield and INSEY was significant in most of the comparisons. In high yielding eastern high clay conventional-till sites, the r^2 was found significant for the relationship between yield and INSEY for all wavelengths. The red-edge NDVI tended have a greater r^2 compared to the red NDVI. The r^2 was also significant at the V6 and V12 growth stages. The r^2 at the V12 stage tended to be greater than the V6.

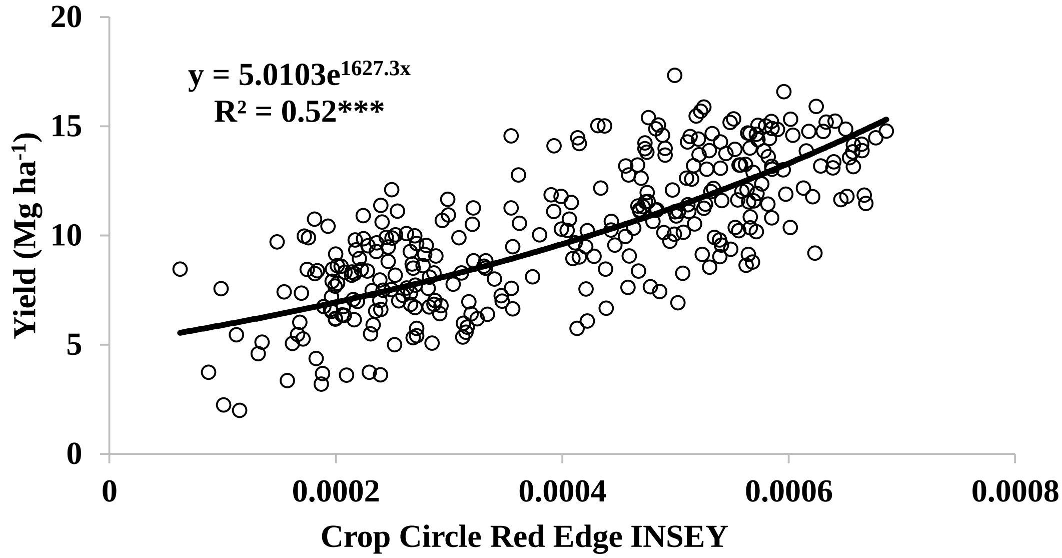

Fig. 5. Crop Circle red-edge INSEY and yield relationship in eastern high clay conventional-till sites with yields atleast one treatment greater than 10 Mg ha^{-1}, 2011, 2012, and 2013. Significance at 0.001 is denoted by †*.**

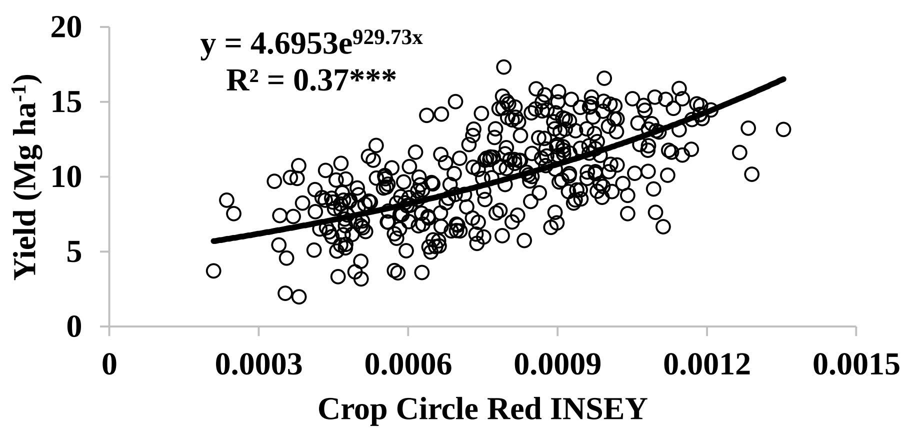

Fig. 6. Crop Circle red INSEY and yield relationship at V6 in eastern high clay conventional-till sites with yields atleast one treatment greater than 10 Mg ha^{-1}, 2011, 2012, and 2013. †* denotes significance at 0.001.**

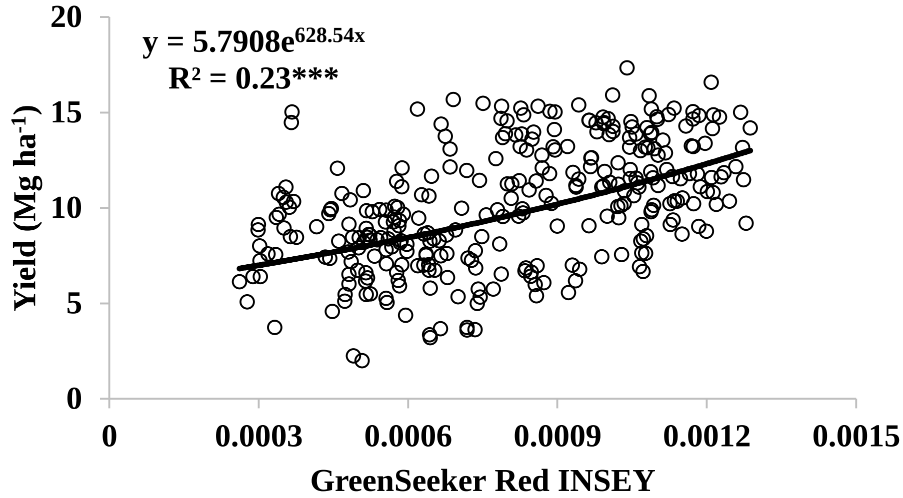

Fig. 7. GreenSeeker red INSEY and yield relationship at V6 in eastern high clay conventional-till sites with yields atleast one treatment greater than 10 Mg ha^{-1}, 2011, 2012, and 2013. Significance at 0.001 is denoted by †*.**

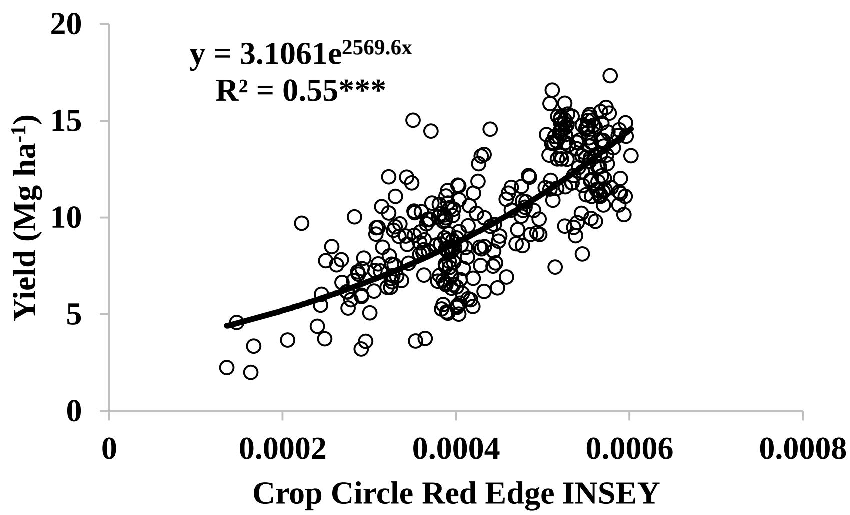

Fig. 8. Crop Circle red-edge INSEY and yield relationship at V12 in eastern high clay conventional-till sites with yields atleast one treatment greater than 10 Mg ha^{-1}, 2011, 2012, and 2013.Significance at 0.001 is denoted by †*.**

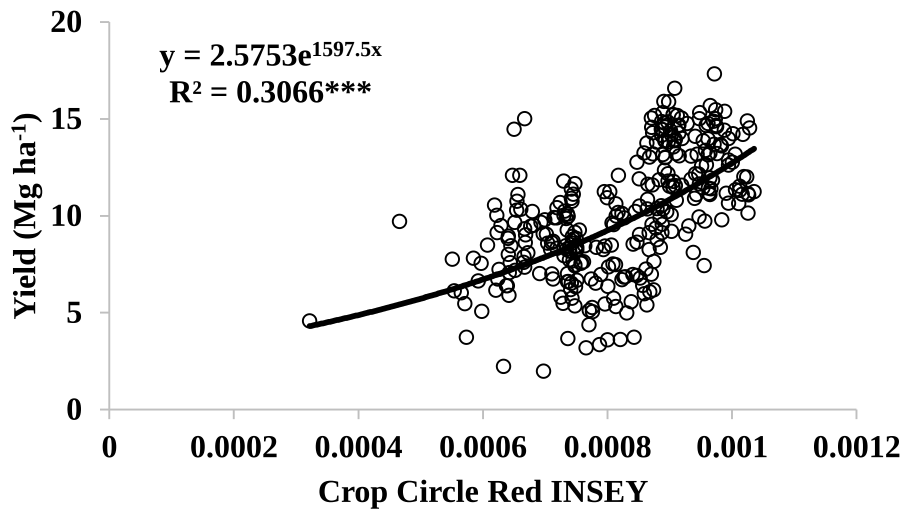

Fig. 9. Crop Circle red INSEY and yield relationship at V12 in eastern high clay conventional-till sites with yields atleast one treatment greater than 10 Mg ha^{-1}, 2011, 2012, and 2013. †* denotes significance at 0.001.**

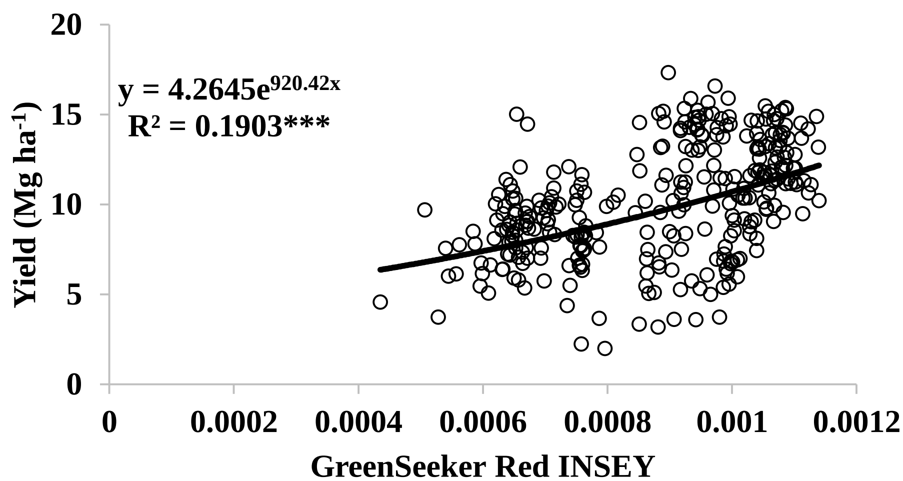

Fig. 10. GreenSeeker red INSEY and yield relationship at V12 in eastern high clay conventional-till sites with yields atleast one treatment greater than 10 Mg ha^{-1}, 2011, 2012, and 2013. †* denotes significance at 0.001.**

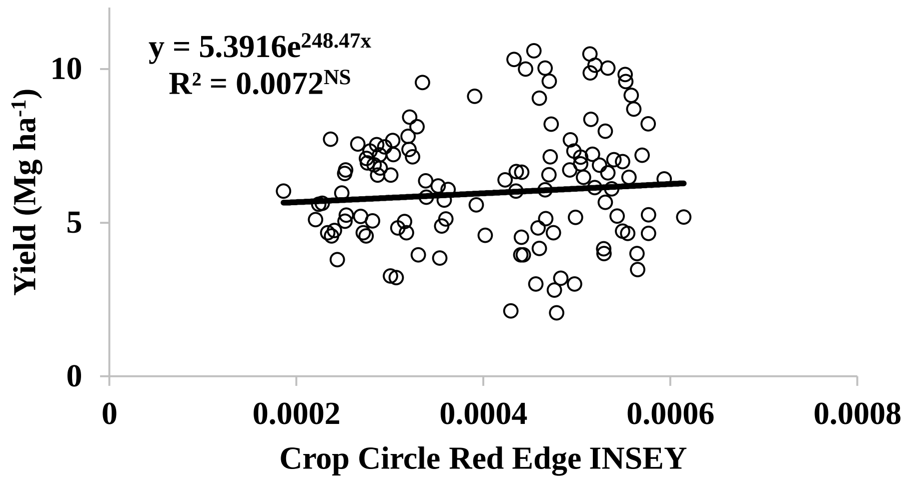

Fig. 11. Crop Circle red-edge INSEY and yield relationship at V6 in eastern high clay conventional-till sites with yields not greater than 10±1 Mg ha^{-1}, 2011, 2012, and 2013.

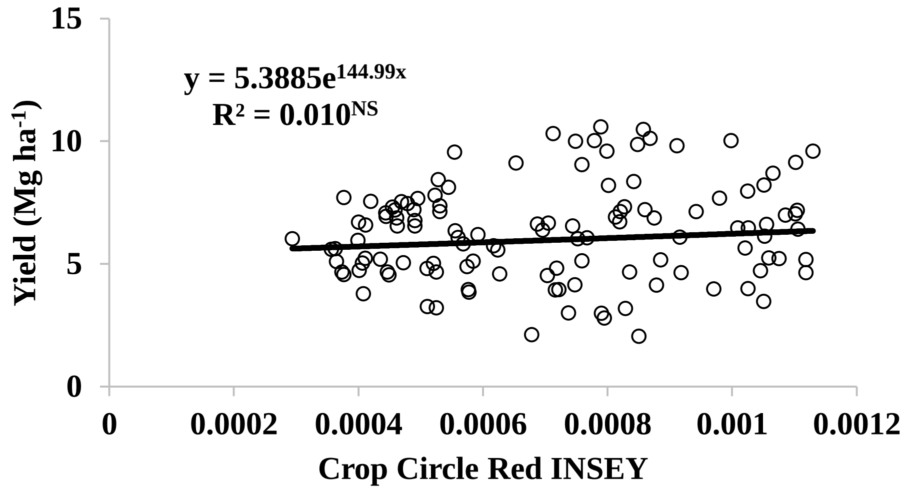

Fig. 12. Crop Circle red INSEY and yield relationship at V6 in eastern high clay conventional-till sites with yields not greater than 10±1 Mg ha^{-1}, 2011, 2012, and 2013.

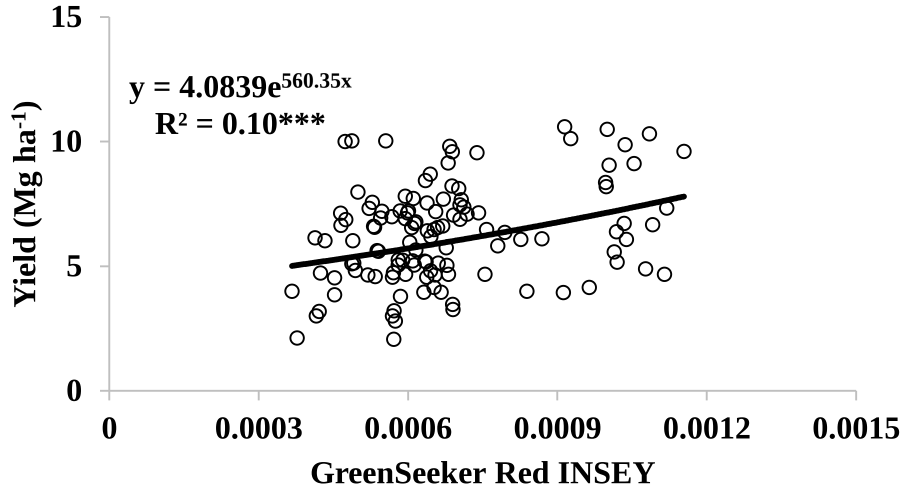

Fig. 13. GreenSeeker red INSEY and yield relationship at V6 in eastern high clay conventional-till sites with yields not greater than 10±1 Mg ha^{-1}, 2011, 2012, and 2013. Significance at 0.001 is denoted by †*.**

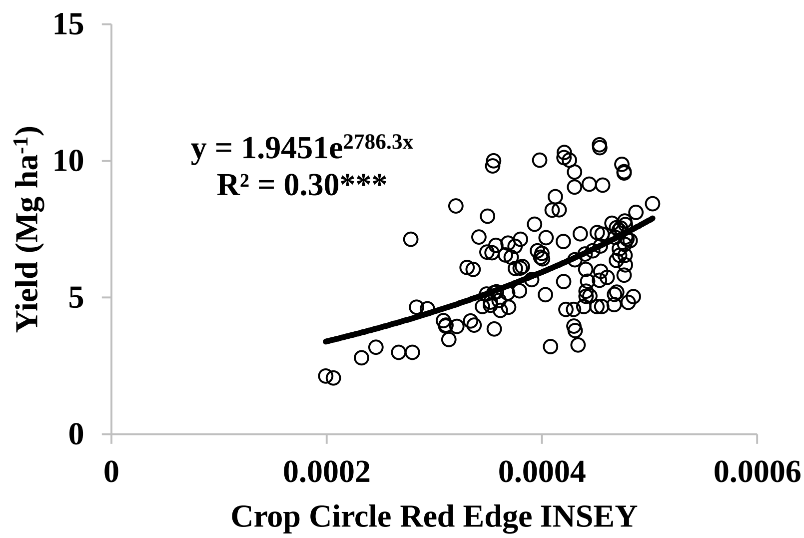

Fig. 14. Crop Circle red-edge INSEY and yield relationship at V12 in eastern high clay conventional-till sites with yields not greater than10±1 Mg ha^{-1}, 2011, 2012, and 2013.Significance at 0.001 is denoted by †*.**

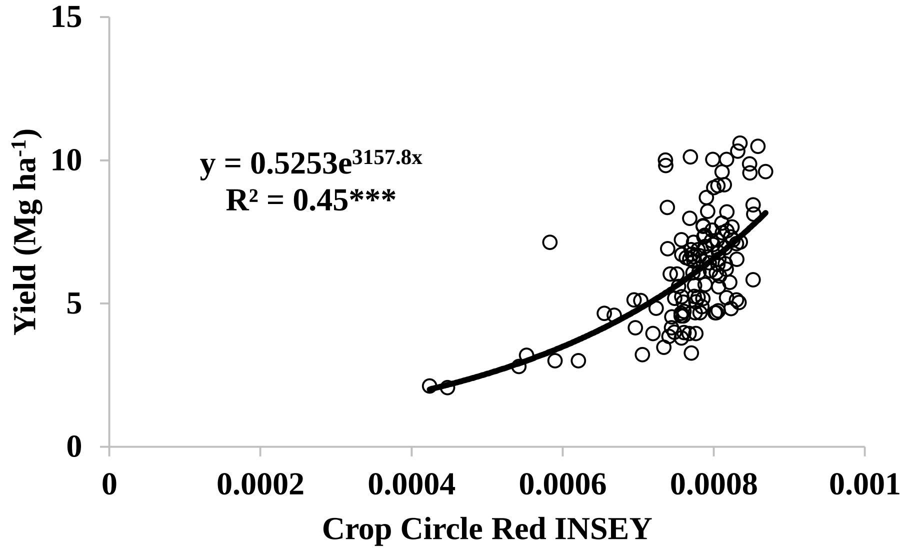

Fig. 15. Crop Circle red INSEY and yield relationship at V12 in eastern high clay conventional-till sites with yields not greater than10±1 Mg ha^{-1}, 2011, 2012, and 2013. Significance at 0.001 is denoted by †*.**

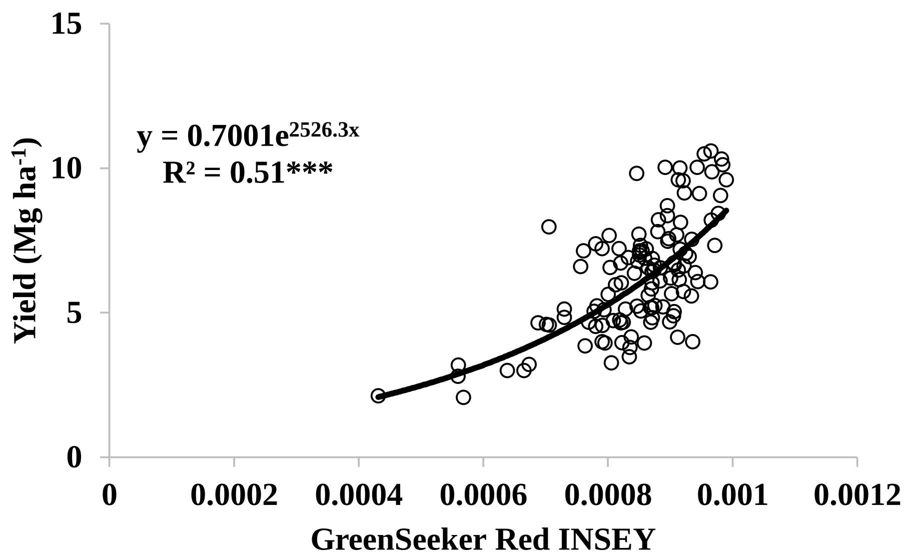

Fig. 16. GreenSeeker red INSEY and yield relationship at V12 in eastern high clay conventional-till sites with yields not greater than 10±1 Mg ha^{-1}, 2011, 2012, and 2013. Significance at 0.001 is denoted by †*.**

Due to difference in N response, all eastern medium-textured conventional-till sites were segregated into high and low yielding sites, with 10 and 10±3 Mg ha^{-1} as the dividing yield, repectively. High yielding eastern medium-textured conventional-till sites had the highest r^2 between INSEY and yield of any category. The r^2 was significant with red INSEY and red-edge INSEY, but red-edge INSEY r^2 tended to higher than red INSEY. The r^2 tended to be higher at V6 compared to the V12 stage. The GS red INSEY was better than the CC Red INSEY at V6, but at V12 the GS red INSEY had the lowest r^2 due to saturation with greater corn biomass. The eastern medium-textured conventional-till sites with yields less than 10 Mg ha^{-1} had low r^2 relating INSEY and yield. This indicated that in these soils loss of N from leaching and denitrification, or late-season drought stress resulted in V6 and V12 sensing values that were only weakly related to yield. West-river sites had significant INSEY and yield r^2 for all sensors and timing. The yield prediction model for eastern no-till sites was found to be better at V12 stage with red wavelength. Due to weak N response at V6 stage there was no relationship between yield and INSEY was able to be calculated with any wavelength. Within the V12 stage, red-edge observed significantly better than other two wavelengths. The GS red wavelength was found weakest at the V12 stage despite the significant regression coefficient of CC red wavelength.

6.4.1. Validation of models

In order to validate the yield prediction models correlation relationship was built between the actual yield and predited yield by the each model described in Table 3. The correlation was positive and significant suggesting that relationship between the actual yield and predicted yield with all the model was strong (Figs 41 to 48). However, the model's correlation line did not fit with 1:1 line. It is important to note that each model predicting the yield under field condition at V6 and V12 despite uncertain environmental conditions changes dramically after V12 such insect-

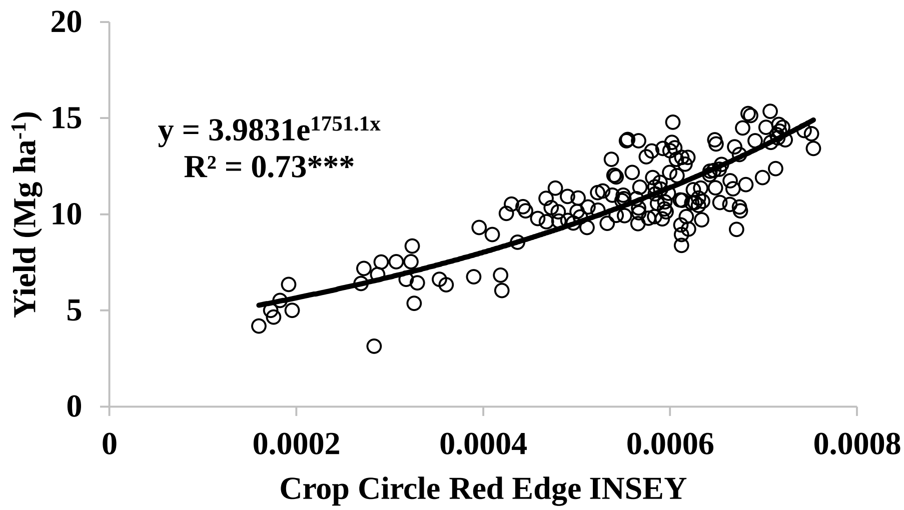

Fig. 17. Crop Circle red-edge INSEY and yield relationship at V6 in medium texture soils with yields atleast on treatment greater than 10 Mg ha^{-1}, 2011, 2012, and 2013. Significance at 0.001 is denoted by †*.**

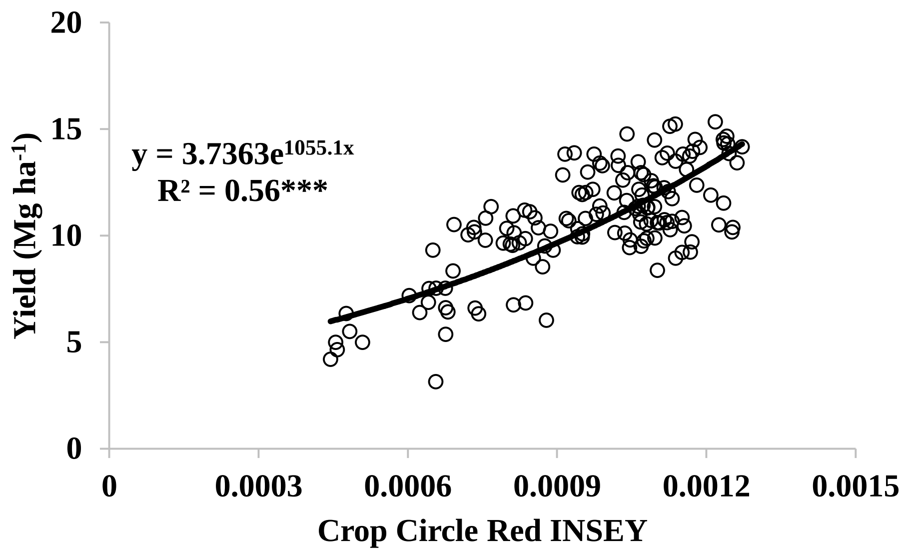

Fig. 18. Crop Circle red INSEY and yield relationship at V6 in medium texture soils with yields atleast on treatment greater than 10 Mg ha^{-1}, 2011, 2012, and 2013. Significance at 0.001 is denoted by †*.**

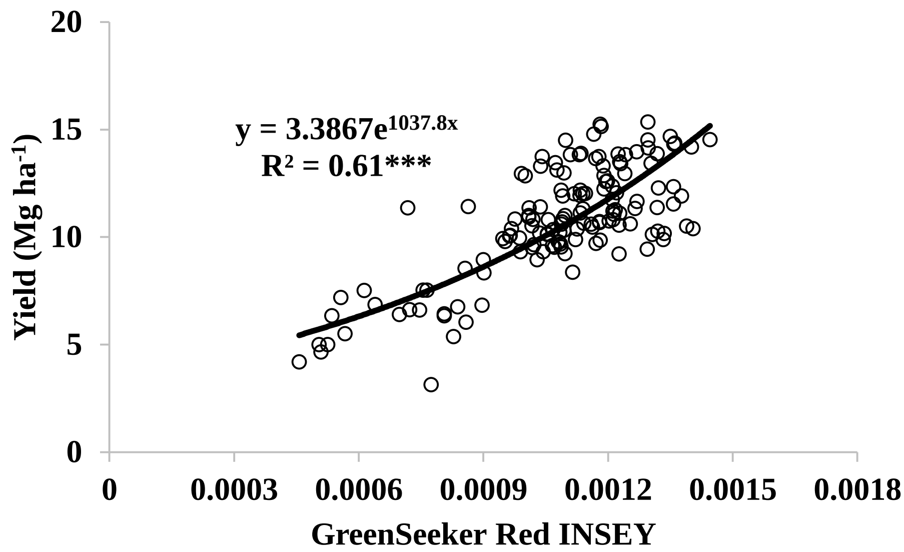

Fig. 19. GreenSeeker red INSEY and yield relationship at V6 in medium texture soils with yields atleast on treatment greater than 10 Mg ha^{-1}, 2011, 2012, and 2013. Significance at 0.001 is denoted by †*.**

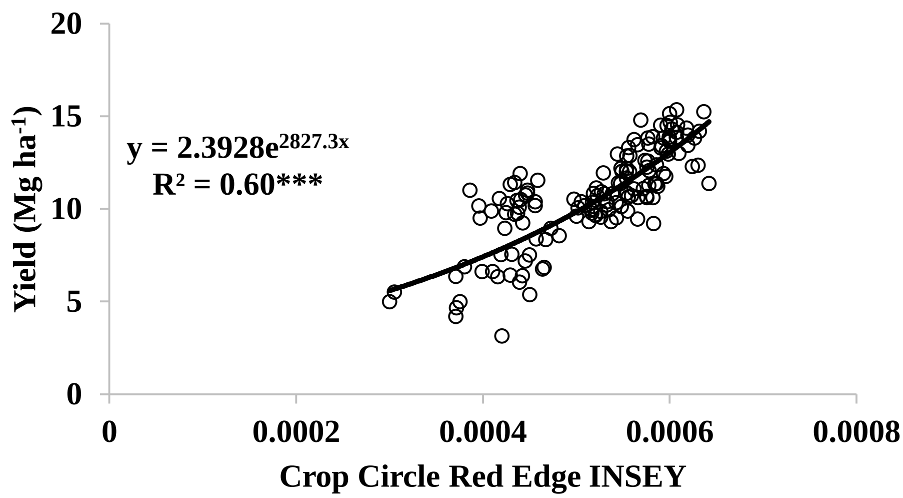

Fig. 20. Crop Circle red-edge INSEY and yield relationship at V12 in medium texture soils with yields atleast on treatment greater than 10±3 Mg ha^{-1}, 2011, 2012, and 2013. Significance at 0.001 is denoted by †*.**

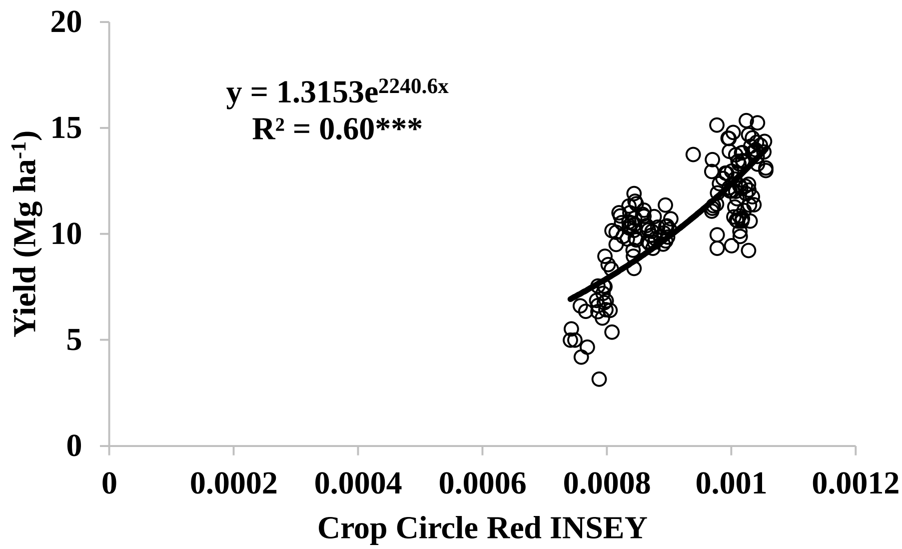

Fig. 21. Crop Circle red INSEY and yield relationship at V12 in medium texture soils with yields atleast on treatment greater than 10±3 Mg ha^{-1}, 2011, 2012, and 2013. Significance at 0.001 is denoted by †*.**

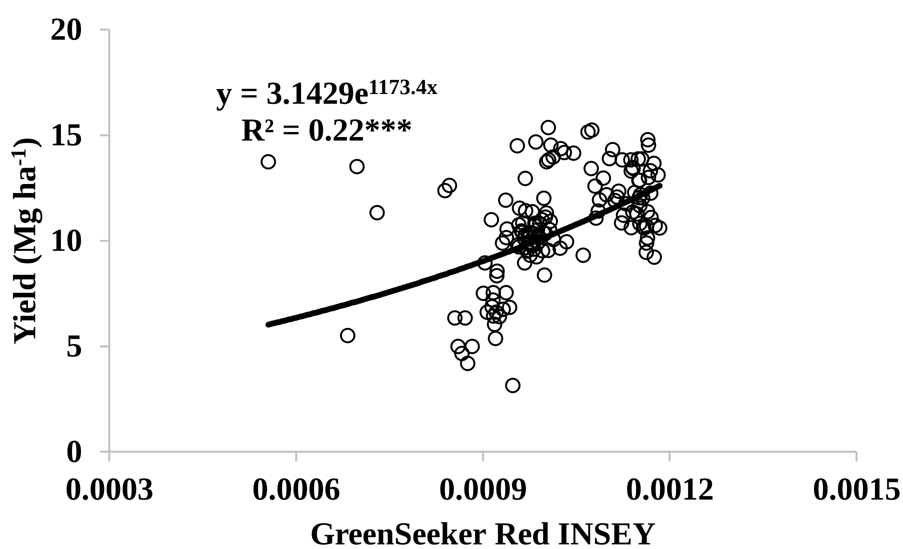

Fig. 22. GreenSeeker red INSEY and yield relationship at V12 in medium texture soils with yields atleast on treatment greater than10±3 Mg ha^{-1}, 2011, 2012, and 2013. Significance at 0.001 is denoted by †*.**

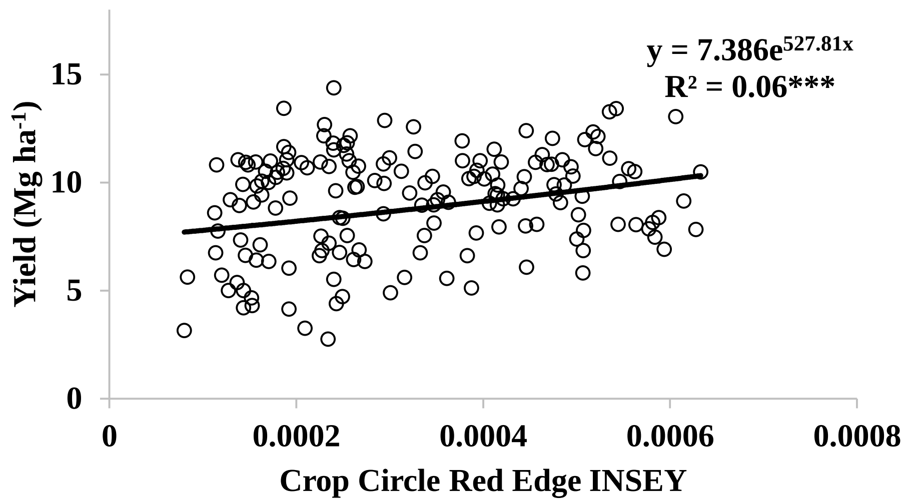

Fig. 23. Crop Circle red-edge INSEY and yield relationship at V6 in medium texture soils with yields not greater than 10±3 Mg ha^{-1}, 2011, 2012, and 2013. Significance at 0.001 is denoted by †*.**

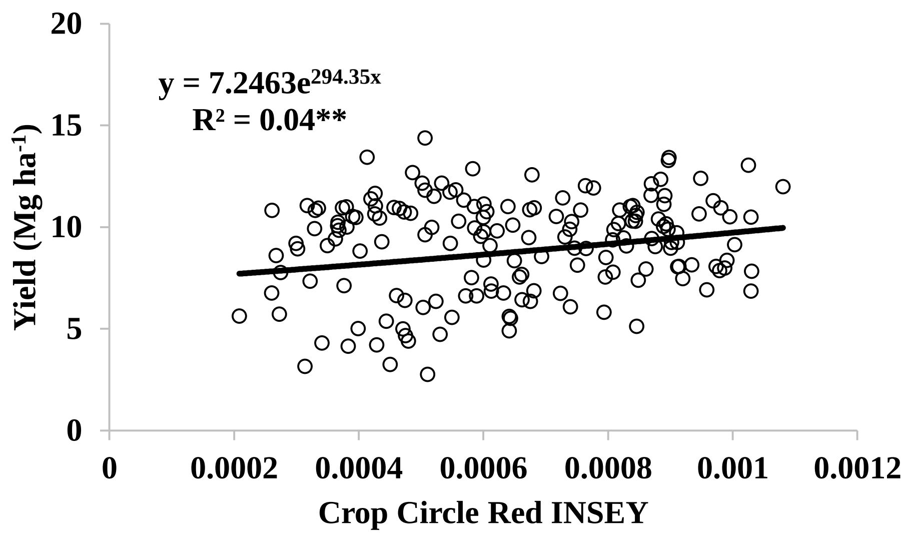

Fig. 24. Crop Circle red INSEY and yield relationship at V6 in medium texture soils with yields not greater than 10±3 Mg ha^{-1}, 2011, 2012, and 2013. Significance at 0.001 is denoted by †*.**

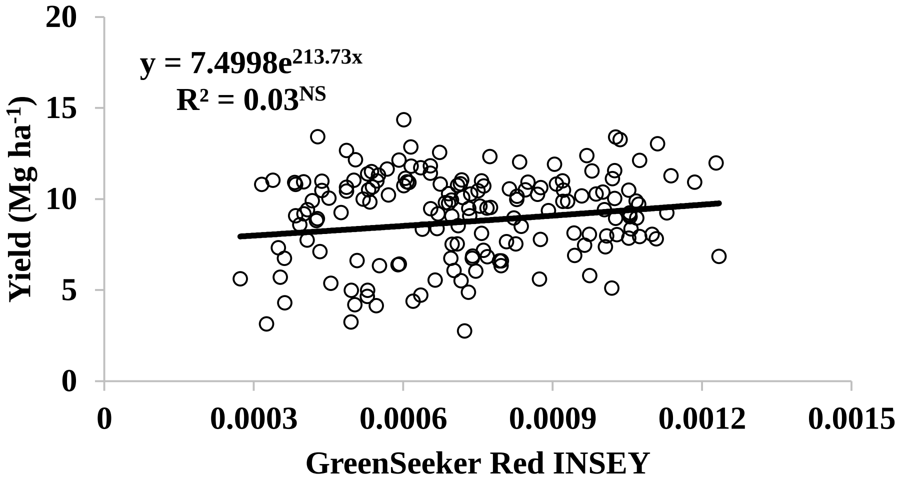

Fig. 25. GreenSeeker red INSEY and yield relationship at V6 in medium texture soils with yields not greater than 10±3 Mg ha^{-1}, 2011, 2012 and 2013.

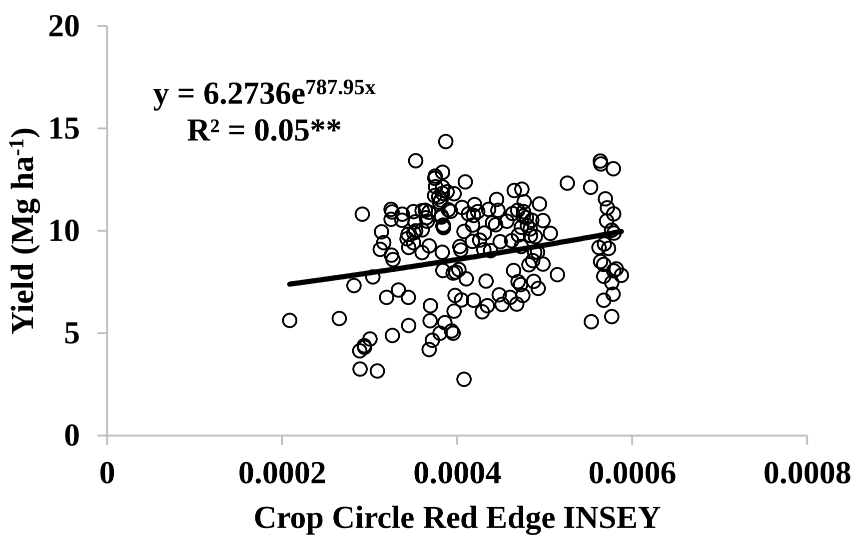

Fig. 26. Crop Circle red-edge INSEY and yield relationship at V12 in medium texture soils with yields not greater than 10±3 Mg ha^{-1}, 2011, 2012 and 2013. Significance at 0.01 is denoted by †.**

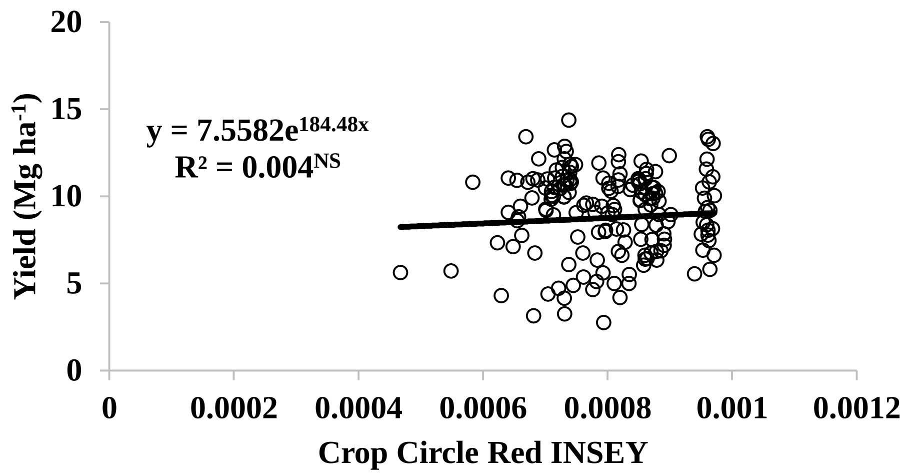

Fig. 27. Crop Circle red INSEY and yield relationship at V12 in medium texture soils with yields not greater than 10±3 Mg ha^{-1}, 2011, 2012 and 2013.

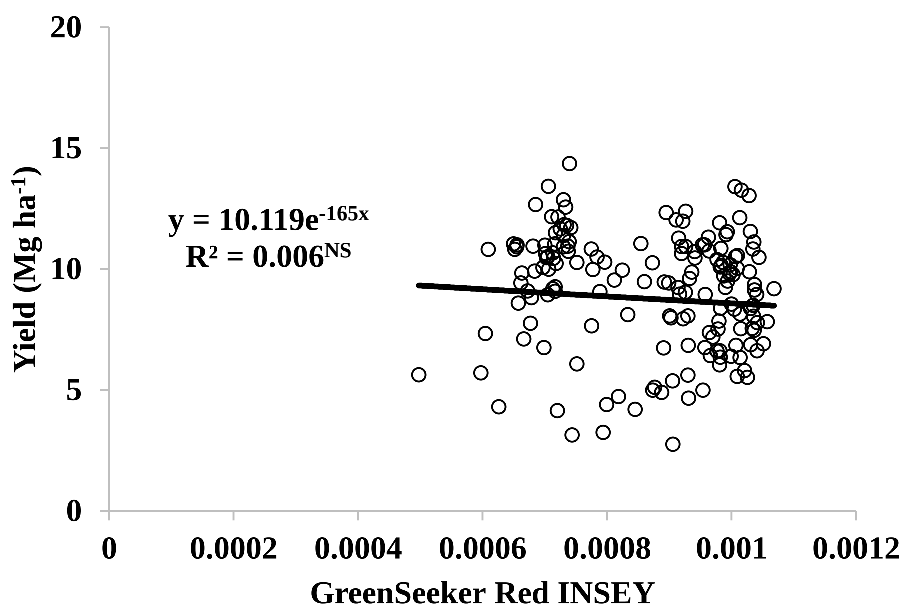

Fig. 28. GreenSeeker red INSEY and yield relationship at V12 in medium texture soils with yields not greater than 10±3 Mg ha^{-1}, 2011, 2012 and 2013.

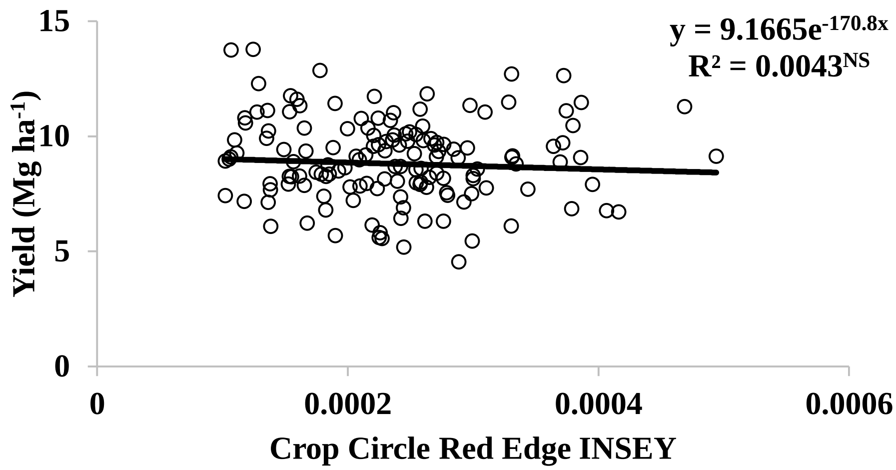

Fig. 29. Crop Circle red-edge INSEY and yield relationship at V6 in eastern North Dakota long-term eastern no-till sites.

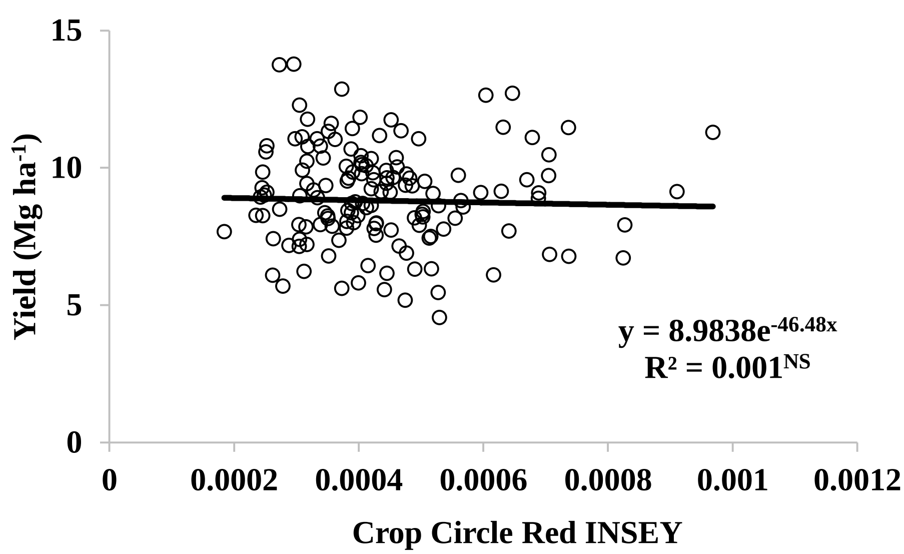

Fig. 30. Crop Circle red INSEY and yield relationship at V6 in eastern North Dakota long-term eastern no-till sites.

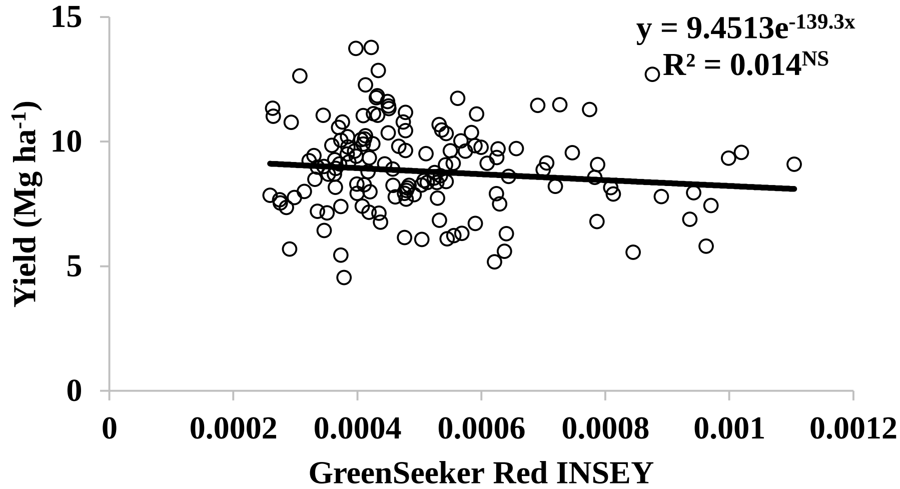

Fig. 31. GreenSeeker red INSEY and yield relationship at V6 in eastern North Dakota long-term eastern no-till sites.

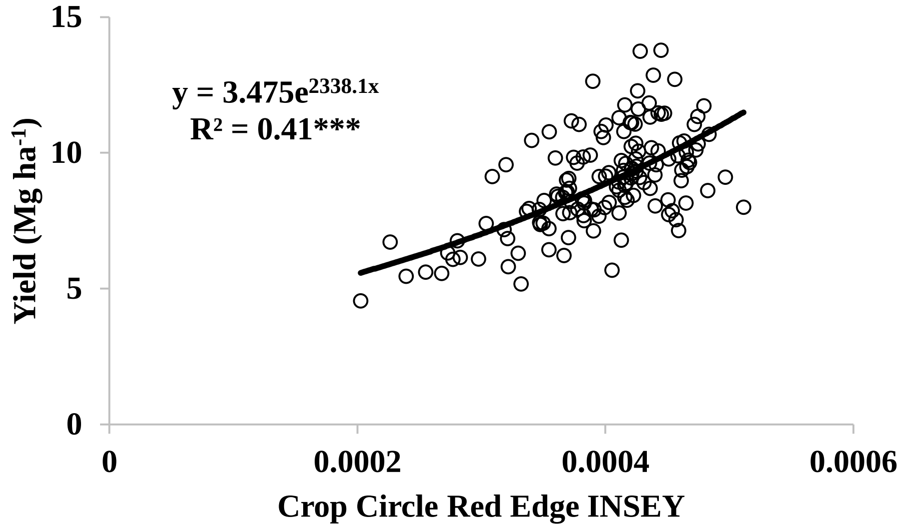

Fig. 32. Crop Circle red-edge INSEY and yield relationship at V12 in eastern North Dakota long-term eastern no-till sites. Significance at 0.001 is denoted by †*.**

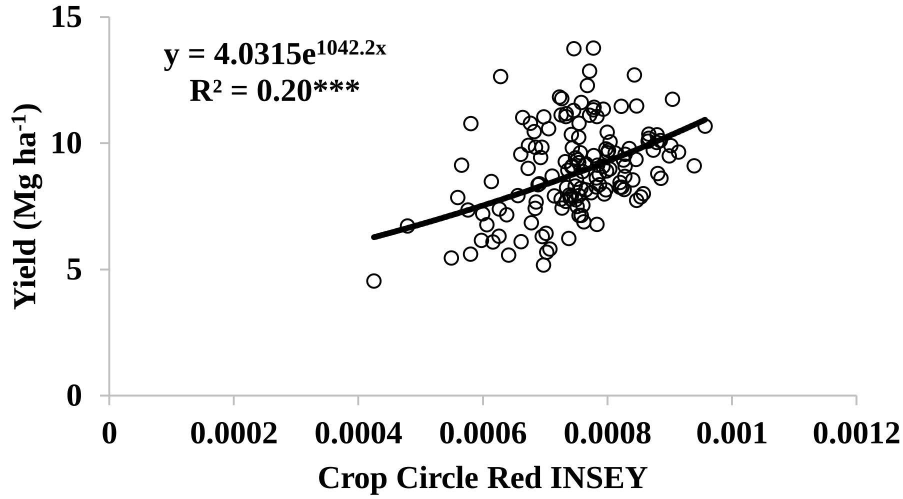

Fig. 33. Crop Circle red INSEY and yield relationship at V12 in eastern North Dakota long-term eastern no-till sites. Significance at 0.001 is denoted by †*.**

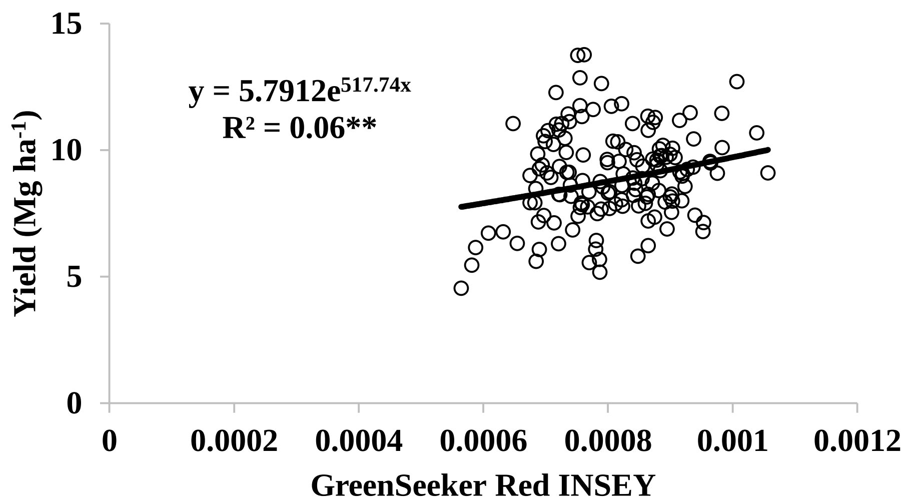

Fig. 34. GreenSeeker red INSEY and yield relationship at V12 in eastern North Dakota long-term eastern no-till sites. Significance at 0.001 is denoted by †*.**

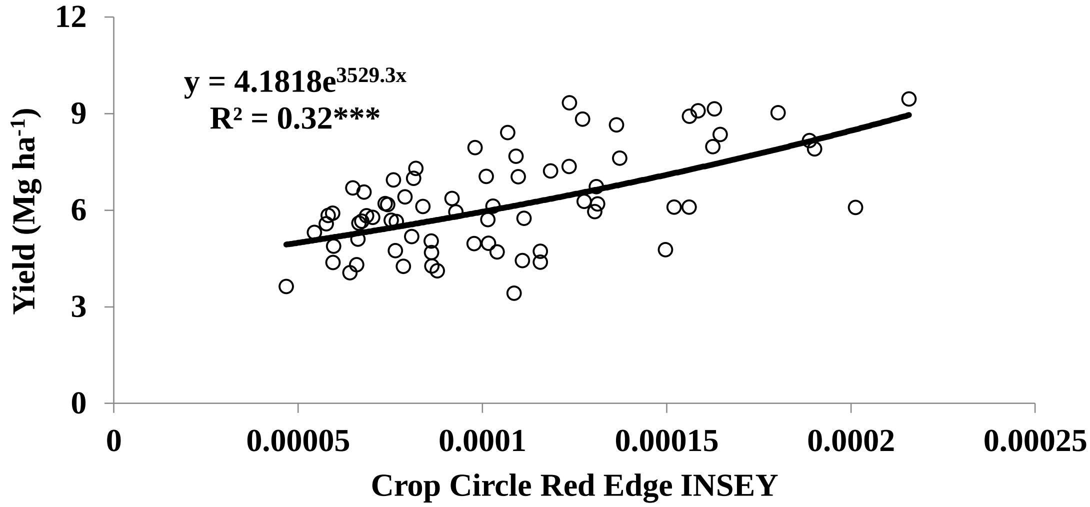

Fig. 35. Crop Circle red-edge INSEY and yield relationship at V6 in west-river North Dakota soils. Significance at 0.001 is denoted by †*.**

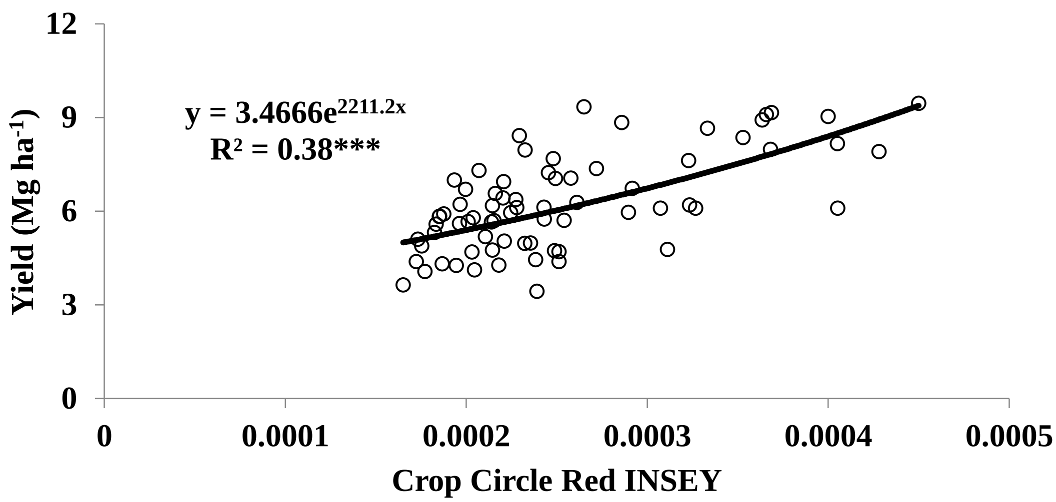

Fig. 36. Crop Circle red INSEY and yield relationship at V6 in west-river North Dakota soils. Significance at 0.001 is denoted by †*.**

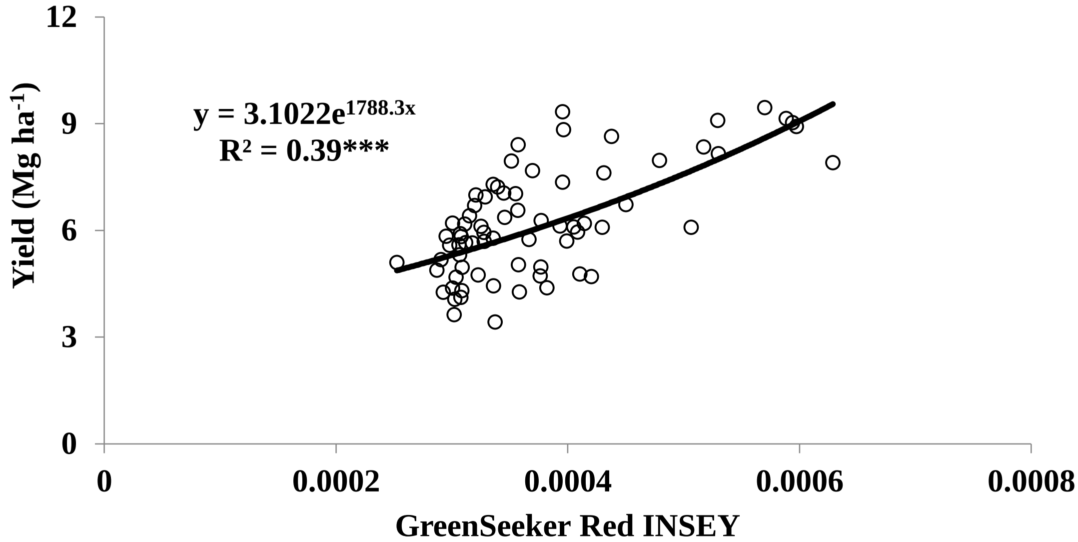

Fig. 37. GreenSeeker red INSEY and yield relationship at V6 in west-river North Dakota soils. Significance at 0.001 is denoted by †*.**

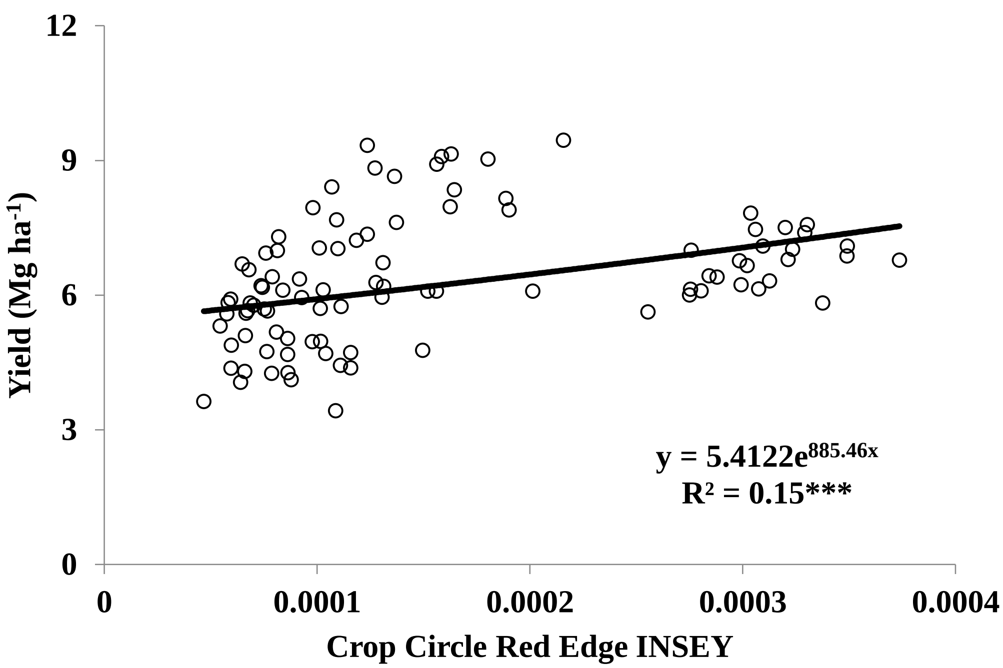

Fig. 38. Crop Circle red-edge INSEY and yield relationship at V12 in west-river North Dakota soils. Significance at 0.001 is denoted by †*.**

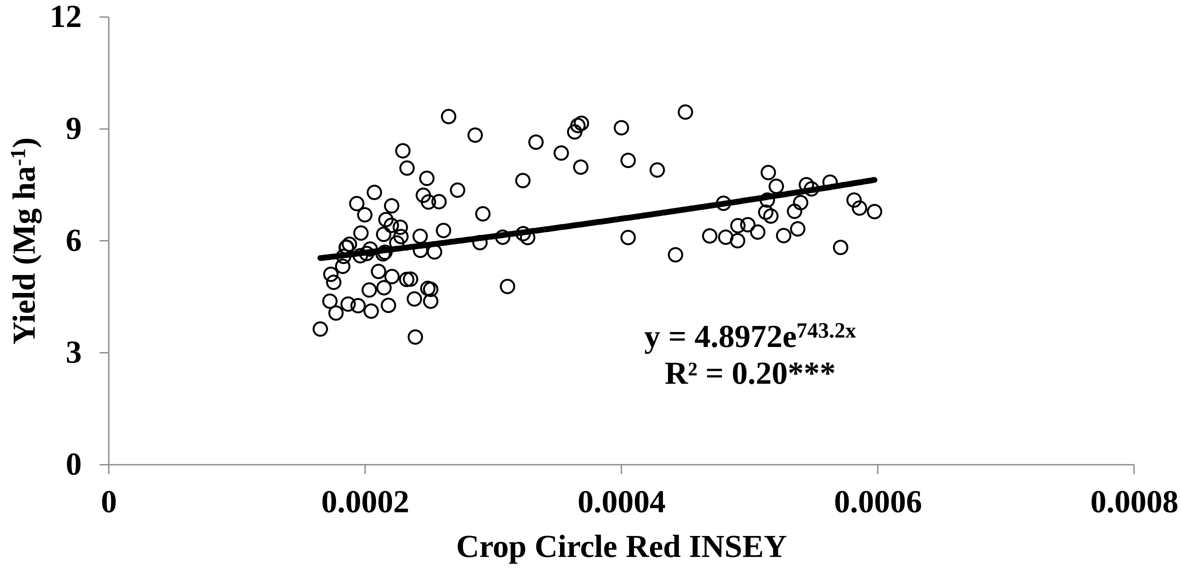

Fig. 39. Crop Circle red INSEY and yield relationship at V12 in west-river North Dakota soils. Significance at 0.001 is denoted by †*.**

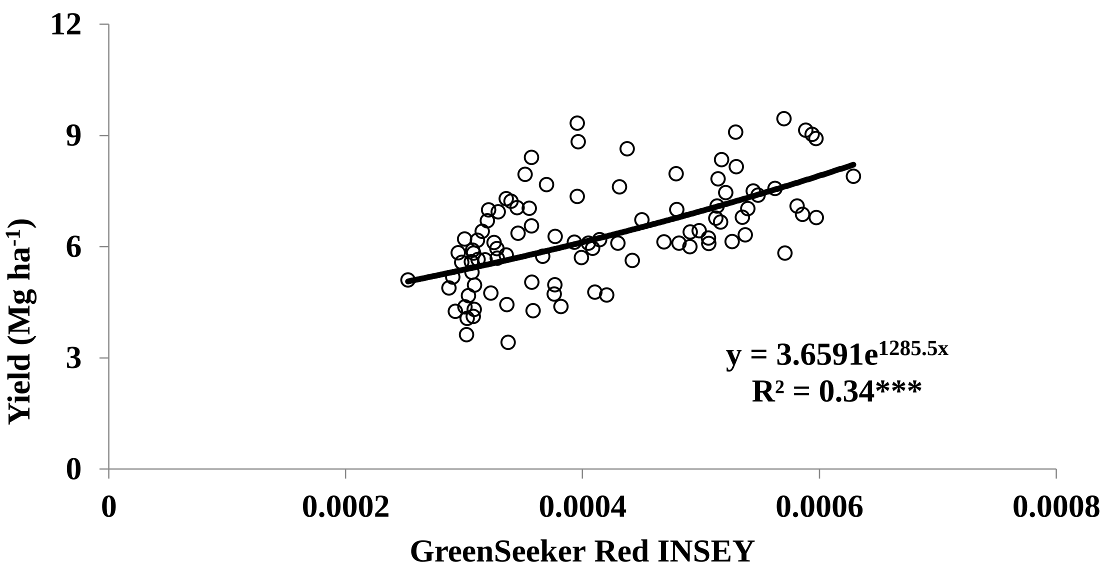

Fig. 40. GreenSeeker red INSEY and yield relationship at V12 in west-river North Dakota soils. Significance at 0.001 is denoted by †*.**

Table 15. Exponential models selected for calculating yield potentials.

Soil category		Crop stage	Sensor type/wavelength	Model†	Sig††
Eastern high clay conventional-till sites	High yielding	V6	Holland Crop Circle/red-edge	$Y=5.0103e^{1627.3x}$	***
		V12	Holland Crop Circle/red-edge	$Y=3.1061e^{2569.6x}$	***
	Low yielding	V6	Use high yielding V6 model	$Y=5.0103e^{1627.3x}$	***
		V12	GreenSeeker/Red	$Y=0.7001e^{2526.3x}$	***
Eastern medium-textured coventional-till sites	High yielding	V6	Holland Crop Circle/red-edge	$Y=3.9831e^{1751.1x}$	***
		V12	Holland Crop Circle/red-edge	$Y=2.3928e^{2827.3x}$	***
	Low yielding	V6	Use high yielding V6 model	$Y=3.9831e^{1751.1x}$	***
		V12	Use high yielding V12 model	$Y=2.3928e^{2827.3x}$	***
Eastern no-till sites		V6	Use west-river sites V6 model	$Y=3.1022e^{1788.3x}$	***
		V12	Holland Crop Circle/red-edge	$Y=3.475e^{2338.1x}$	***
West-river sites		V6	GreenSeeker/Red	$Y=3.1022e^{1788.3x}$	***
		V12	GreenSeeker/Red	$Y=3.6591e^{1285.5x}$	***

†Symbol ^{X} in model=INSEY (sensor reading/growing degree days from planting to sensing).
††* denotes significance at 0.001**

pest damge, drought, and hail. The value of correlation confirms that sensors ability to predict the corn yield is strong especially CC red-edge wavelength out performed over all the wavelengths used in two sensors. Although the models perfomed efficiently but there is still chance t oimprove it by decreasing the errors of different paramers added to it such as programming the models to take the data from growers field while they are using the models.

The red wavelength yield prediction model differs due to the range of wavelength used in two sensors. A weak yield and INSEY relationship at V6 stage under eastern no-till sites might be due to slower early corn growth (Hoeft et al., 1999). Also in eastern no-till sites sensor readings might not be the actual reflection from N response instead it represent the poor plant growth due to wetter and cooler conditions. A yellowing of corn leaves was observed during V6 and V12 stage, which could be a reason for low weak red-edge relationship. Excessive reflectance of NIR from residue is also a problem.

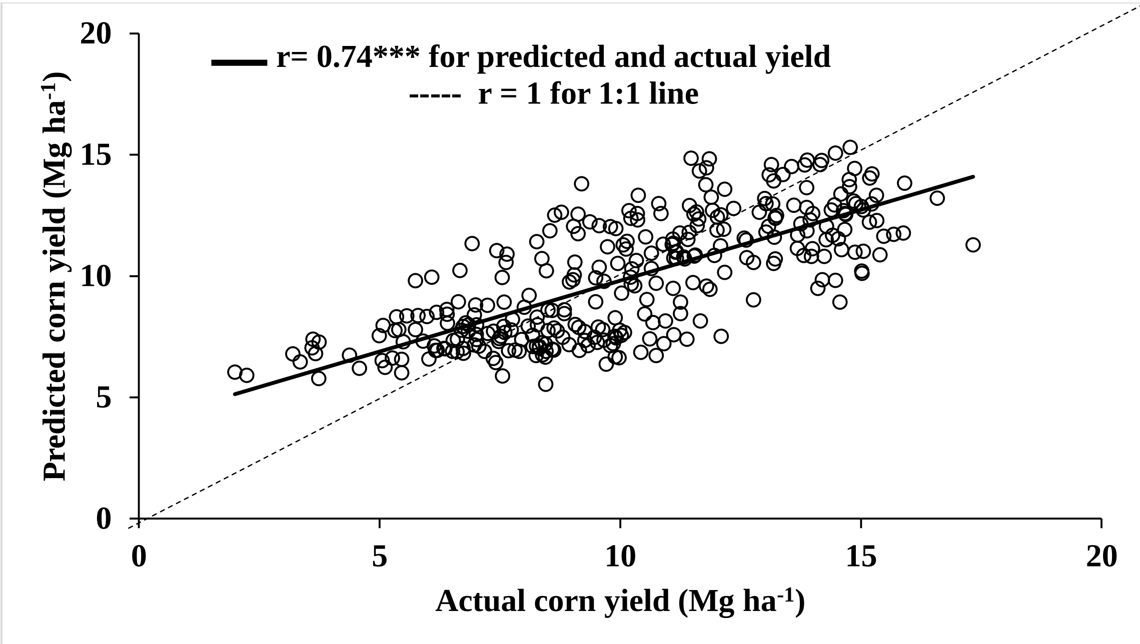

Fig. 41. Correlation between actual yield and predicted yield by CC red-edge model at V6 stage of eastern high clay conventional-till sites with yield at least from one treatment more than 10 Mg ha^{-1}. Significance at 0.001 is denoted by †*.**

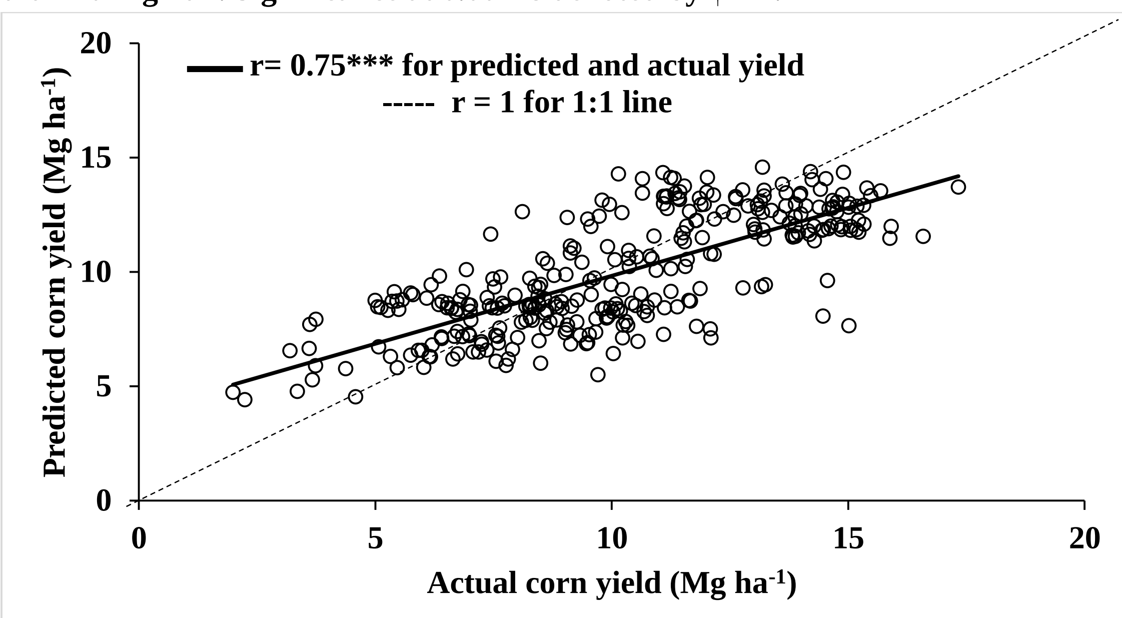

Fig. 42. Correlation between actual yield and predicted yield by CC red-edge model at V12 stage of eastern high clay conventional-till sites with yield at least from one treatment more than 10 Mg ha^{-1}. Significance at 0.001 is denoted by †*.**

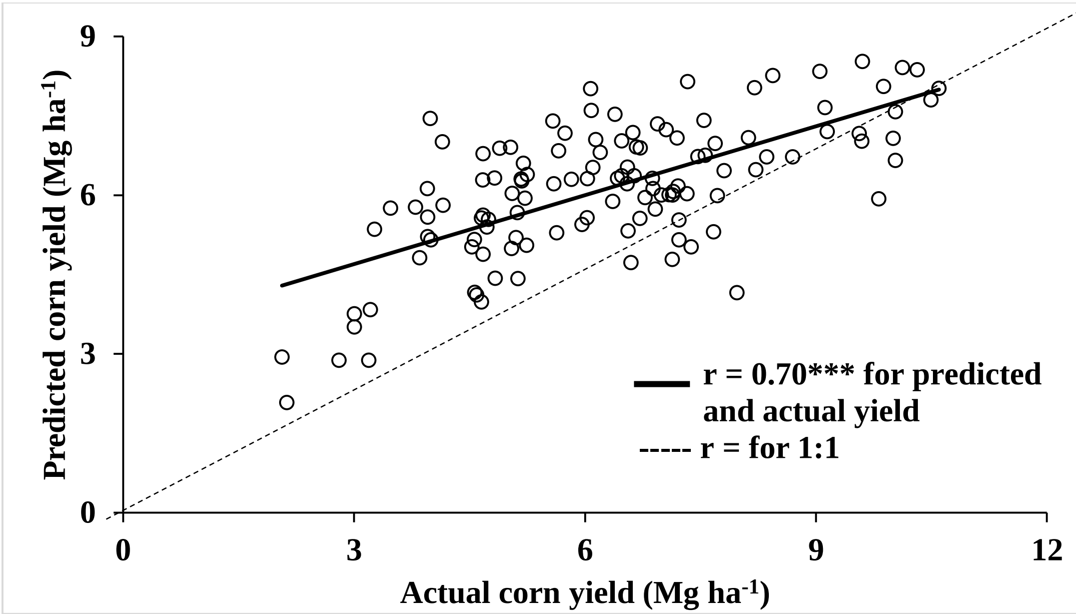

Fig. 43. Correlation between actual yield and predicted yield by GS red model at V12 stage of eastern high clay conventional-till sites with yield at not greater than 10±1 Mg ha^{-1}. Significance at 0.001 is denoted by †*.**

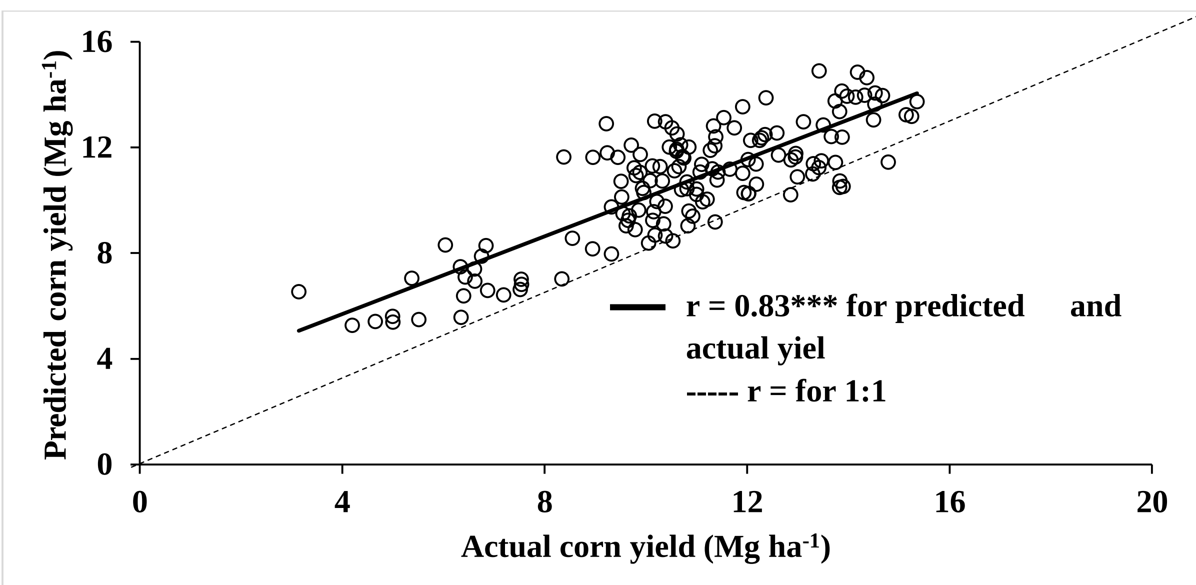

Fig. 44. Correlation between actual yield and predicted yield by CC red-edge model at V6 stage of eastern medium-textured conventional-till sites with yield at least from one treatment more than 10 Mg ha^{-1}. Significance at 0.001 is denoted by †*.**

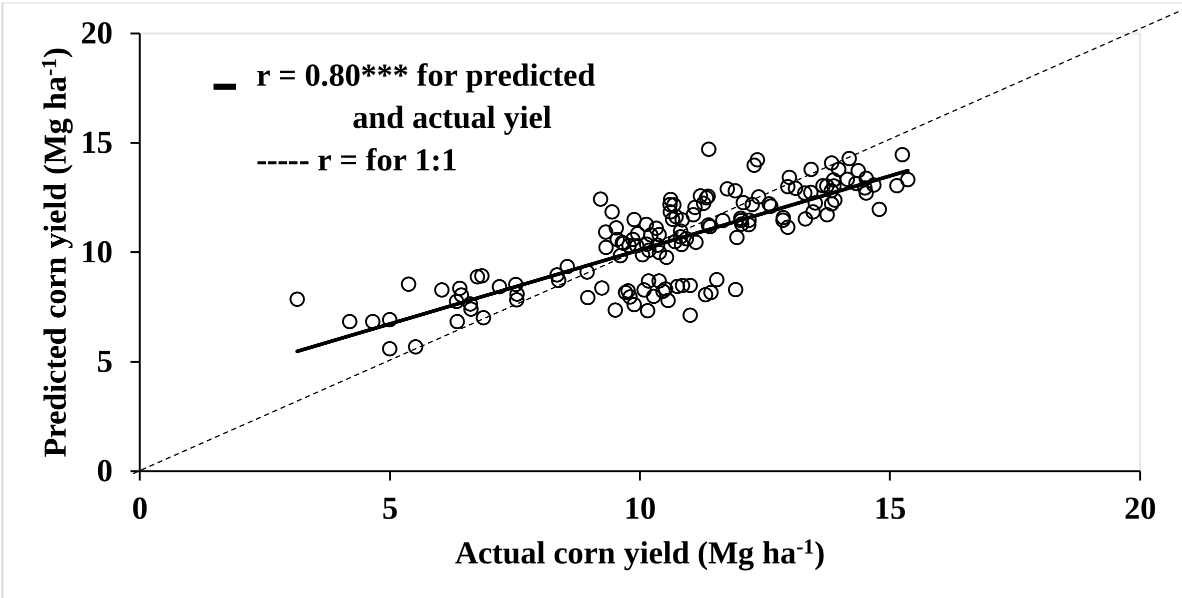

Fig. 45. Correlation between actual yield and predicted yield by CC red-edge model at V12 stage of eastern medium-textured conventional-till sites with yield at least from one treatment more than 10 Mg ha^{-1}. Significance at 0.001 is denoted by †*.**

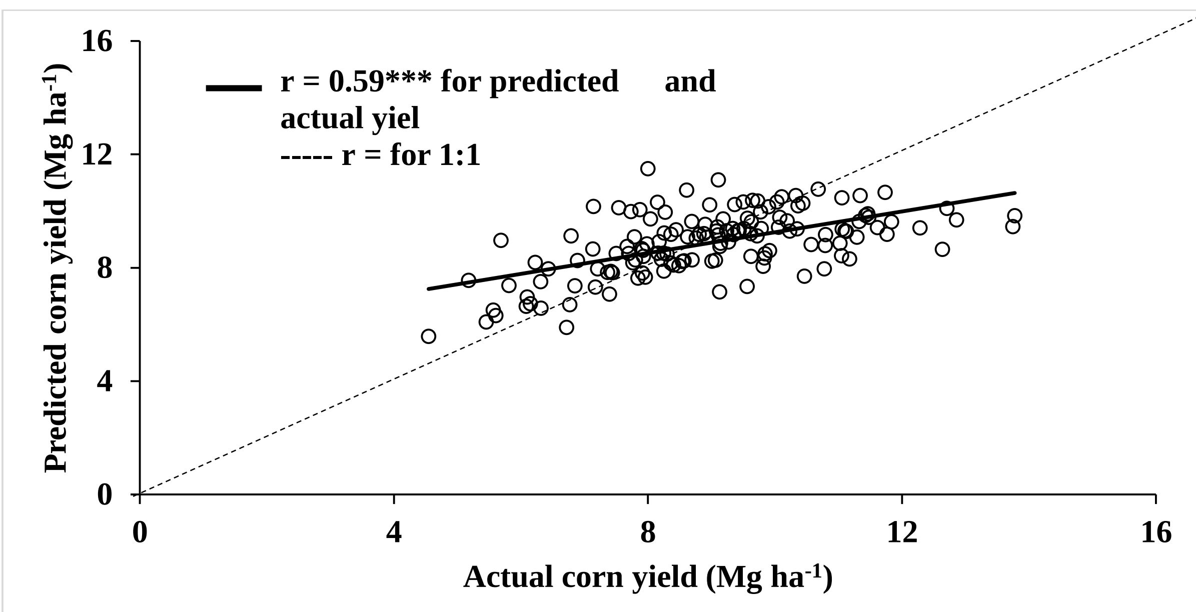

Fig. 46. Correlation between actual yield and predicted yield by CC red-edge model at V12 stage of eastern no-till sites. Significance at 0.001 is denoted by †*.**

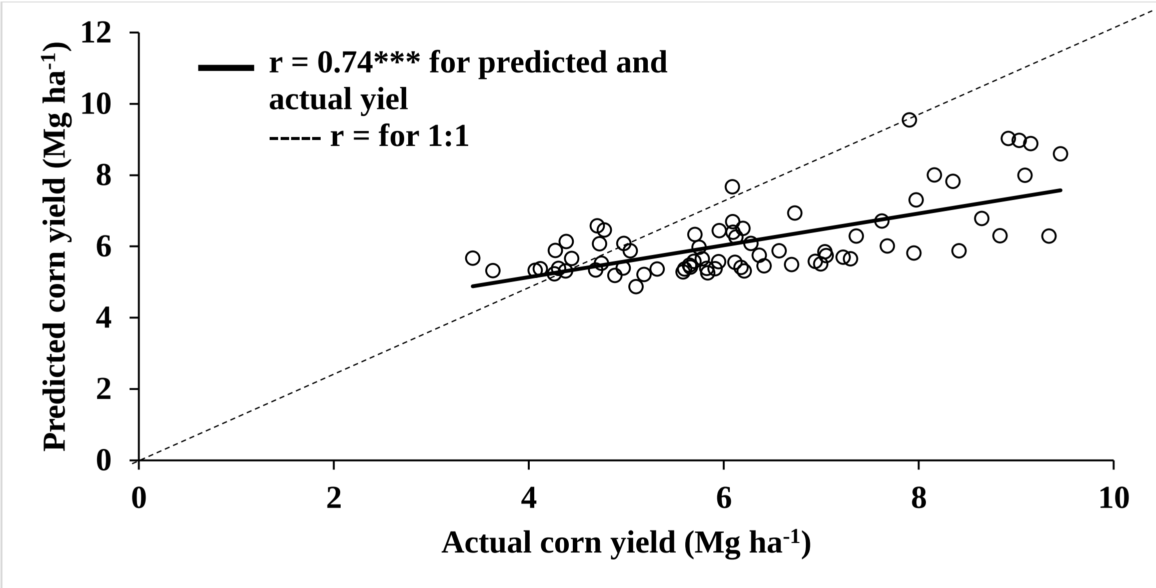

Fig. 47. Correlation between actual yield and predicted yield by GS red model at V6 stage of west-river sites. Significance at 0.001 is denoted by †*.**

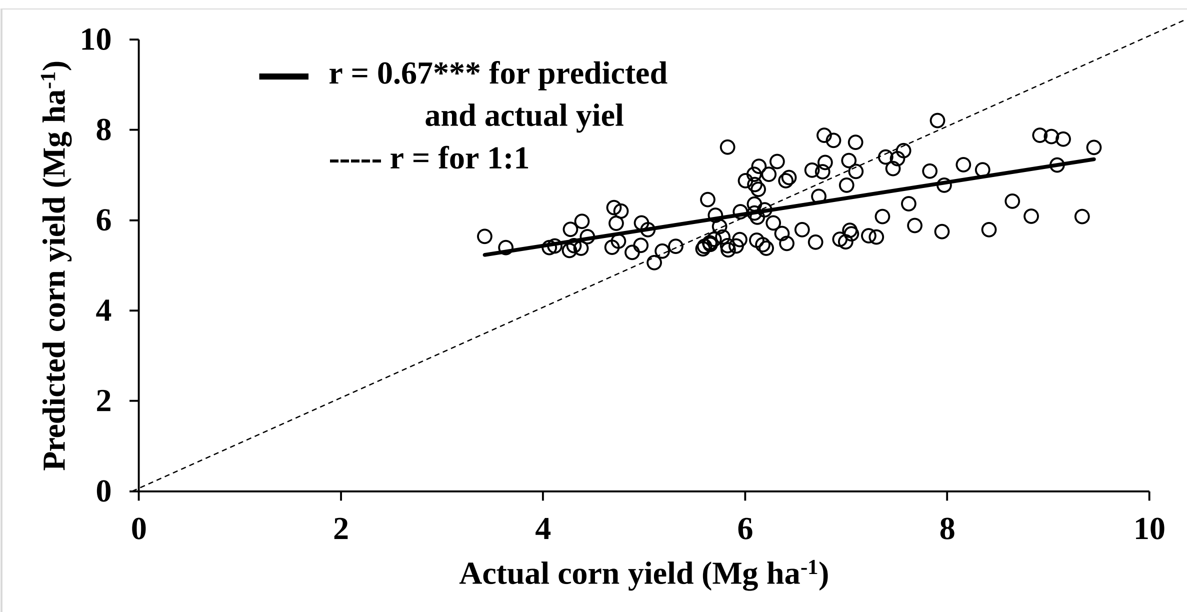

Fig. 48. Correlation between actual yield and predicted yield by GS red model at V12 stage of west-river sites. Significance at 0.001 is denoted by †*.**

6.5. Discussion

6.5.1. Procedure to use algorithm

A N rich strip needs to be established within a variety within an algorithm category in every field. The N rich strip could be applied when a base rate of N, directed by zone soil sampling in North Dakota is applied. The strip could be any width with length at least 30 m. When the in-season applicator enters the field at about V6, the rate controller will have the INSEY vs Yield regression model (Table 13) programmed into the rate equation. The N rich strip sensing will serve as the predictor of Y1.

As the applicator moves through the field, readings are accumulated at a length of row typically the distance from sensor to point of application, perhaps 6 m to 10 m depending on the application equipment. As the sensor readings are integrated, yield prediction *Y2* is determined. The predicted amount of N required to move *Y2* to *Y1* will be:

$$N\ predicted\ in\ kg/ha = \frac{[(Y1 - Y2)\ X\ 0.0125]}{0.6}$$

Where:

Y1 is the yield prediction from the N-rich strip in kg ha^{-1}

Y2 is the yield predicted in an area of the field just sensed in kg ha^{-1}

1.25% (0.0125) is factor representing percent N in corn grain (Raun et al., 2002).

0.6 is a common efficiency factor (60%) for an in-season below soil surface N application. The efficiency factor might be decreased if the application is on the soil surface and not incorporated, particularly if the soil conditions are very dry.

Our procedure differs from the use of response index (RI). Response index is calculated by dividing the high N plot NDVI by the NDVI from check plot. Response index is important in algorithms that use a limited data base and in variable soils and conditions. The reason we chose not to use a response index was that we already categorized the algorithm within separate environments (east and west), soil textures (eastern high clay conventional-till sites and eastern medium-textured conventional-till sites), and cultural practices (eastern and west-river no-till sites). Therefore, we have segregated variation due to different N responses under different soils and cultural practices.

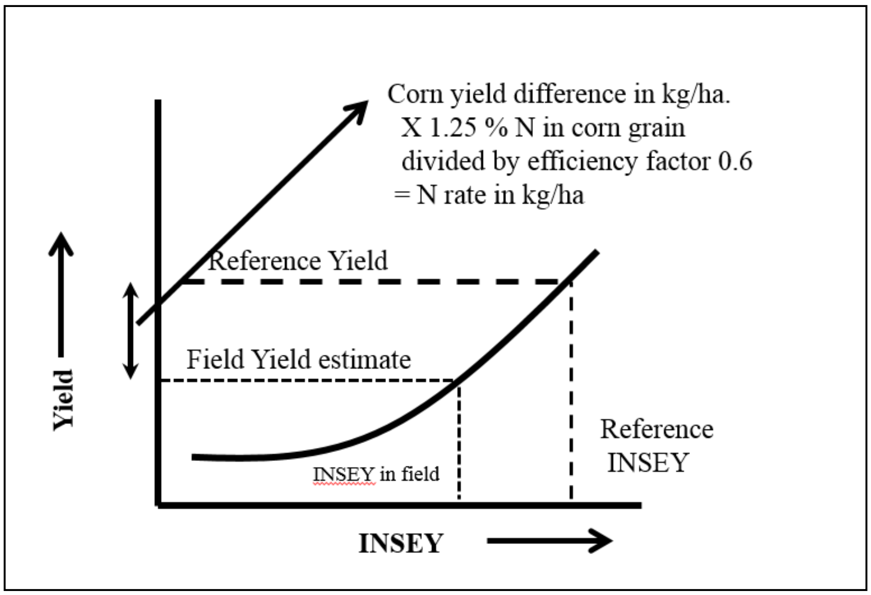

Fig. 49. Example of using N calculation though our sensor based algorithm.

The GS and CC sensor use are similar in their yield prediction ability. At V6, both red INSEY and red-edge INSEY could be used. At V12, the red-edge INSEY is nearly always superior.

6.6. Conclusion

The algorithms produced through the present study could give more precise in-season N rate calculations than other conventional sensor based algorithms because specific soil or cultivation systems have been considered while building the N rate algorithm whereas other researchers gave more gerneralized N rate models. Two sensing times (V6 and V12) have been found to give significant estimation of yield. The V6 sensing was found weaker than V12 and no relationship was detected under low yielding eastern high clay conventional-till sites, eastern medium-textured coventional-till sites and eastern no-till sites, whereas V12 was found weak only under low yielding eastern medium-textured coventional-till sites. The weak relationship in the lower yielding eastern high clay conventional-till sites and eastern medium-textured coventional-till sites was probably the result of denitrification in the eastern high clay conventional-till sites and leaching in the eastern medium-textured coventional-till sites. These results indicate that in practice, the algorithms for the higher yielding eastern high clay conventional-till sites and eastern medium-textured coventional-till sites should be used, since application at V6 would often be made after the seasonal N loss period was over. The weak relationship between yield and sensor INSEY at long-term eastern no-till sites is might be due to slower growth in cooler soils, with the sensors underestimating yield potential therefore, delaying supplemental N application about V12 would not be expected to hold back yield, and algorithms developed by V12 would help capture higher yields through late in-season N application. Three wavelength combinations provided good relationships with yield. the value of regression coefficient confirmed that the red-edge wavelength (730nm) generally performed better than the other two red wavelengths, 656 and 670nm, from GS and CC, respectively at V12, and the red-edge was similar to the red wavelengths at V6.

6.7. Literature Cited

Bandel, V.A., S. Dzienia, and G. Stanford. 1980. Comparison of N fertilizers for no-till sites corn. Agron. J. 72:337-341.

Biermacher, J.T., F.M. Epplin, B.W. Brorsen, J.B. Solie, and W.R. Raun. 2006. Maximum benefit of a precise nitrogen application system for wheat. Precis. Agric., 7: 1–12.

Binford, G.D., A.M. Blackmer, and M.E. Cerrato. 1992a. Relationships between corn yields and soil nitrate in late spring. Agron. J. 84, 53-59.

Boyer, J.S. 1982. Plant productivity and the environment. Science. 218:443-448.

Bundy, L.G. 2000. Nitrogen recommendations and optimum nitrogen rates: How do they compare? p. 5–13. *In* Proc. North Central Ext.-Industry Soil Fertil. Conf., St. Louis, MO. Vol. 16. Potash and Phosphate Inst., Brookings, SD.

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

CAST. 1999. Gulf of Mexico hypoxia: Land and sea interactions. Task Force Report No. 134. Council for Agricultural Science and Technology, Ames, IA.

Chappelle, E.W., M.S. Kim, and J.E. McMurtrey III. 1992. Ratio analysis of reflectance spectra (RARS): an algorithm for the remote estimation of the concentrations of Chlorophyll A, Chlorophyll B, and Carotenoids in soybean leaves. Remote Sens. Environ. 39:239-247

Dobermann, A., J.L. Ping, V.I. Adamchuk, G.C. Simbahan, and R. Ferguson. 2003. Classification of crop yield variability in irrigated production fields. Agron. J. 95: 1105-1120.

Dobermann, A., and K. G. Cassman. 2002. Plant nutrient management for enhanced productivity in intensive grain production systems of the United States and Asia. Plant Soil 247: 153-175.

Eghball, B. J.S. Schepers, M. Negahban, and M.R. Shaver. 2003. Spatial and temporal variability of soil nitrate and corn yield: multifractal analysis. Agron. J. 95:339-346.

Fageria, N.K., and V.C. Baligar. 2005. Enhancing nitrogen use efficiency in crop plants, Adv. Agron. Vol. 88. 97-185.

Ferguson, R.B., R.M. Lark, and G.P. Slater. 2003. Approaches to management zone definition for use of nitrification inhibitors. Soil Sci. Soc. Am. J. 67:937-947.

Ferguson, R.B., R.M. Lark, and G.P. Slater. 2003. Approaches to management zone definition for use of nitrification inhibitors. Soil Sci. Soc. Am. J. 67:937-947.

Fox, R.H., J.M. Kern, and W.P. Piekielek. 1986. Nitrogen fertilizer source and method and time of application effects on no-till corn yields and N uptakes. Agron. J. 78:741-746.

Franzen, D. W. 2010. North Dakota fertilizer recommendation tables and equations. NDSU Extension Circular SF-882. North Dakota State University Extension Service, Fargo, ND.

Franzen, M. 2012. Program for initial analysis of GreenSeeker_ and Holland Crop Circle_ Sensor raw data within Excel. Unpublished program. Fargo, ND.

Franzen, D.W., D.H. Hopkins, M.D. Sweeney, M.K. Ulmer, and A.D. Halvorson. 2002. Evaluation of soil survey scale for zone development of site-specific nitrogen management. Agron. J. 94:381-389.

Gausman, H. W. 1974. Leaf reflectance of near-infrared. Photogram. Eng. Remote Sens. 40:183-191.

Gausman, H. W. 1977. Reflectance of leaf components. Remote Sens. Environ. 6:1-9.

Gitelson A.A., and M.N. Merzlyak. 1997. Remote estimation of chlorophyll content in higherplant leaves. J. Remote Sens. 18:2691-2697.

Goos, R.J., and L. Prunty. 1990. Yield variability and the yield goal decision. p. 187-189. *In* J.L. Havlin (ed.) Proc. of the Great Plain Soil Fertility Conf., Denver, CO. 6-7 Mar. 1990. Kansas State Univ., Manhattan.

Herrmann, A., and F. Taube. 2004. The range of the critical nitrogen dilution curve for maize (Zea mays L.) can be extended until silage maturity. Agron. J. 96:1131-1138.

Hoeft, R.G., E.D. Nafaziger, R.I. Mulvuney, L.C. Gonzini, and J.J. Warren. 1999. Effect of tme and rate of N application on N use efficiency and surface water contamination with nitrate, In: Hoeft, R.G. (ed). 1999. Illinois Fertilizer Conference Proceedings, pp. 39-54.

Holland, K.H., and J.S. Schepers. 2010. Derivation of a Variable Rate Nitrogen Application Model for In-Season Fertilization of Corn. Agron. J. 102:1415-1424.

Horler, D.N.H., M. Dockray, and J. Barber. 1983. The red-edge of plant leaf reflectance. Int. J. Remote Sens. 4:273-288.

Jaynes, D.B., and T.S. Colvin. 1997. Spatiotemporal variavility of corn and soybean yield. Agron. J. 89:30-37.

Jiang, P., and K.D. Thelen. 2004. Effects of soil and topographic properties on crop yield in a north-central corn-soybean cropping system. Agron. J. 96:252-258.

Johnston, A.E. 2000. Efficient use of nutrients in agricultural production systems. Commun. Soil. Sci. Plant Anal. 31:1599–1620.

Kachanoski, R.G., I.P. O'Halloran, D. Aspinall, and P.Von Bertoldi. 1996. Delta yield: Mapping fertilizer nitrogen requirement for crops. Better Crops 80:20–23.

Kravchenko, A.N., G.P. Robertson, K.D. Thelen, and R.R. Harwood. 2005. Management, topographical, and weather effects on spatial variability of crop grain yields. Agron. J. 97:514-523.

Kravchenko, A.N., D.G. Bullock, and H.F. Reetz. 2000. Correlation of corn and soybean grain yield with topography and soil properties. Agron. J. 92:75–83.

Lambert, D.M., J. Lowenberg-DeBoer, and G.L. Malzer. 2006. Economic analysis of spatial-temporal patterns in corn and soybean response to nitrogen and phosphorus. Agron. J. 98:43-54.

Lindsay, W.L., and W.A. Norvell.1978. Development of a DTPA soil test for zinc, iron, manganese, and copper. Soil Sci. Soc. Am. J. 42:421–428.

Lory, J.A., Scharf, P.C., 2003. Yield goal versus delta yield for predicting fertilizer nitrogen need in corn. Agron. J. 95:994-999.

Maddux, L.D., D.E. Kissel, and P.L. Barnes. 1984. Effects of nitrogen placement and application on irrigated corn. J. Fert. Issues 1:86-89.

Meghji, M.R., J.W. Dudley, R.J. Lambert, and G.F. Sprague. 1983. Inbreeding depression, inbred and hybrid grain yields, and other traits of maize genotypes representing three eras. Crop Sci. 24:545-549.

Mengel, D.B., D.W. Nelson, and D.M. Huber. 1982. Placements of nitrogen fertilizers for no-till and conventional till corn. Agron. J. 74:515-518.

Olsen, S.R., C.V. Cole, F.S. Watanabe, and L.A. Dean.1954b. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circular 939. U.S. Government Printing Office, Washington, D.C.

Ortiz-Monasterio, J.I. and W.R. Raun. 2007. Reduced nitrogen and improved farm income for irrigated spring wheat in the Yaqui Valley, Mexico, using sensor based nitrogen management. J. Agric. Sci., 145, 1–8.

Plénet, D., and G. Lemaire. 1999. Relationships between dynamics of nitrogen uptake and dry matter accumulation in maize crops. Plant Soil. 216:65-82

Rabalais, N.N. 2002. Nitrogen in aquatic ecosystems. Ambio 31:102-112.

Raun, W.R. and G.V. Johnson. 1999. Improving nitrogen use efficiency for cereal production. Agron. J. 91:357–363.

Rice, C.W., and J.L. Havlin. 1994. Integrating mineralizable nitrogen indices into fertilizer nitrogen recommendations. p. 1-13. *In* J.L. Havlin *et al.* (ed.) Soil testing: Prospects for improving nutrient recommendations. SSSA Spec. Publ. 40. SSSA, Madison, WI.

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, R.W. Mullen, K.W. Freeman, W.E. Thomason, and E.V. Lukina. 2002. Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. Agron. J. 94:815-351.

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

Schepers, J.S., and A.R. Mosier. 1991. Accounting for nitrogen in nonequilibrium soil-crop systems. p. 125-138. *In* R.F. Follett *et al*. (eds.) Managing nitrogen for groundwater quality and farm profitability. SSSA, Madison, WI.

Schepers, A.R., J.F. Shanahan, M.A. Liebig, J.S. Schepers, S.H. Johnson, and A. Jr Luchiari. 2004. Appropriateness of management zones for characterizing spatial variability of soil properties and irrigated corn yields across years. Agron. J. 96:195-203.

Schilling, K.E. 2002. Chemical transport from paired agricultural and restored prairie watersheds. J. Environ. Qual. 31:1184-1193.

Schröder, J.J., J.J. Neeteson, O. Oenema, and P.C. Struik. 2000. Does the crop or the soil indicate how to save nitrogen in maize production? Reviewing the state of the art. Field Crops Res. 66, 277-278.

Schulte, E.E., and B.G. Hopkins. 1996. Estimation of soil organic matter by weight-loss-on ignition. In F.R. Magdoff et al. (Eds.), Soil Organic Matter: Analysis and Interpretation (Chap. 3, pp. 21–31). SSSA Special Publication 46. Madison, WI: SSSA.

Slaton, M.R., E.R. Hunt, and W.K.Smith. 2001. Estimating near-infrared leaf reflectance from leaf structural characteristics. Am. J. Bot. 88:278-284.

Steinheimer, T.R., K.D. Scoggin, and L.A. Kramer. 1998. Agricultural chemical movement through a field size watershed in Iowa: Surface hydrology and nitrate losses in discharge. Env. Sci. Tech. 32:1048-1052.

Teal, R.K., B. Tubana, K. Girma, K.W. Freeman, D.B. Arnall, O. Walsh, and W.R. Raun. 2006. In-season prediction of corn grain yield potential using normalized difference vegetation index. Agron. J. 98: 1488–1494.

Thomas, G.W. 1982. Exchangeable cations. In A. L. Page et al. (Eds.). Methods of soil analysis. Part 2. Agronomy Monographs 9, pp. 159–165. Madison, WI: ASA and SSSA.

Tubana, B.S., D.B. Arnall, O. Walsh, B. Chung, J.B. Solie, K. Girma, and W.R. Raun. 2008. Adjusting midseason nitrogen rate using a sensor-based optimization algorithm to increase use efficiency in corn. J. Plant Nutr. 31:1393–1419.

Tollenaar, M. 1989. Genetic improvement in grain yield of commercial maize hybrids grown in Ontario from 1959 to 1988. Crop Sci. 29:1365-1371.

Turner, R.E., Rabalais, N.N., 1991. Changes in Mississippi river water-quality this century. Bioscience 41:140-147.

Vanderlip, R. L. and D. L. Fjell. 1994. Use of growing degree units in corn production. In: Corn Production Handbook (pp. 6-8). Manhattan, KS: Kansas State University Agricultural Experiment Station and Cooperative Extension Service C-560.

Vanotti, M.B., and L.G. Bundy. 1994. Corn nitrogen recommendations based on yield response data. J. Prod. Agric. 7:249-256.

United States Department of Agriculture-National Agricultural Statistics Service. 2003. Statistics of Fertilizers and Pesticides [Online].

Available at http://www.usda.gov/nass/pubs/agr03/03_ch14.pdf (Verified 26 Apr. 2004).

Watson, D., and J.R. Brown. 1998. pH and lime requirement. In Brown, J. R. (ed.) Recommended Chemical Soil Test Procedure for the North Central Region. North Central Regional Res. Pub. No. 221 (revised). Missouri Agric. Exp. Stat. SB 1001, Univ. of Missouri, Columbia, p. 13.

CHAPTER VII. USE OF N-RICH STRIP AND GROUND BASED ACTIVE OPTICAL SENSORS TO DETECT SULFUR DEFICIENCIES IN CORN

7.1. Abstract

Prediction of S deficiency in the soil is difficult due to its interaction with nitrogen. The use of non-destructive sensors have used to determine plant nutrient status and several indices have been developed to detect the nutrient deficiency through ground based active-optical (GBAO) sensors by using different wavelength combinations. The objective of the study was to compare two active optical sensor for their ability to detect S deficiency in corn at two leaf stages (V6 and V12). Two GBAO sensors GS and CC were used on two experimental sites with established corn N-rate trials in North Dakota at the V6 and V12 growth stages in 2013. Randomized complete block design with four replications and six N rate treatments. Both the sensors were found useful in detecting the S deficiency in corn, particularly at V6 stage.

Key Words: Sulfur, NDVI, nitrogen

7.2. Introduction

In the USA, soil sulfur (S) levels are decreasing in part due to decreased emissions from gaseous S emitting industries, such as coal-fired power plants (Schwab, 2008). Figure 1 and 2 represents the S deposition over the years. Sulfur (S) is required for crop production because of its many roles in plants, including it is a component of proteins as the amino acids cystine, cysteine, and methionine, and over 100,000 known secondary plant S compounds, including flavonoids, carotenoids, chlorophylls and glucosinolates (Barker and Pilbeam, 2007 p. 183-225).

Plant available S is in the sulfate form. Sulfates are soluble in water, so its movement with water deeper into the soil beyond the reach of roots results in deficiency. Sulfur deficiency is most common in coarser textured soils. Sulfur deficiency is also more common in lower organic matter soils on higher landscape positions (Franzen, 2010).

The rate of photosynthesis is directly related to the amount of light absorption, which is related to chlorophyll content (Maas and Dunlap, 1989; Gates et al., 1964; Hatfield et al., 2008). Chlorophyll content changes in response to plant developmental stage or stress and `measuring chlorophyll content can be a useful tool for evaluating plant health. Gitelson et al. (1997) evaluated the vegetative indices of multiple species and determined that reflectance and absorption of light in the 530-630 nm and near 700 nm wavelengths were related to chlorophyll content. Light reflectance of plant tissue at the specific wavelengths of 700 and 550 nm were highly correlated with chlorophyll content ($r^2 > 0.97$). Wavelengths in the near infrared spectrum (750-900nm) were relatively insensitive to chlorophyll content. An index was established for predictive measurements using the ratio of the 750 nm light reflectance to the 550 nm wavelength. Leaf spectral properties are also related to leaf morphology and physiology, including thickness of leaf (Gausman and Allen, 1973), N content (Walburg et al., 1982), water content (Gausman et al., 1971), and chlorophyll concentration (Gausman, 1982; Ercoli et al., 1993). Plants with deficiency of N, P, K, S, and Mg absorb less light and reflect more light in the visible spectrum (400-700 nm) compared to normal plants (A1-Abbas et al., 1974). A study on *Hosta ventricosa* and soybean *(Glycine max* L.) showed that with deficiency of Co, Ni, Zn, As, and P, reflection in the visible spectrum 500-600nm increases (Milton et al., 1989 and 1991) and red-edge range (690-730nm) shifts to a shorter wavelength (Horler et al., 1983; Adams et al., 1993). Masoni et al. (1996) after evaluating Fe, S, Mg, and Mn deficiencies in corn found that leaf chlorophyll concentrations decreased with decreasing micronutrient concentration. Chlorophyll *a* concentration was 22% less when Fe, Mg, or Mn were deficient compared to unstressed plants.

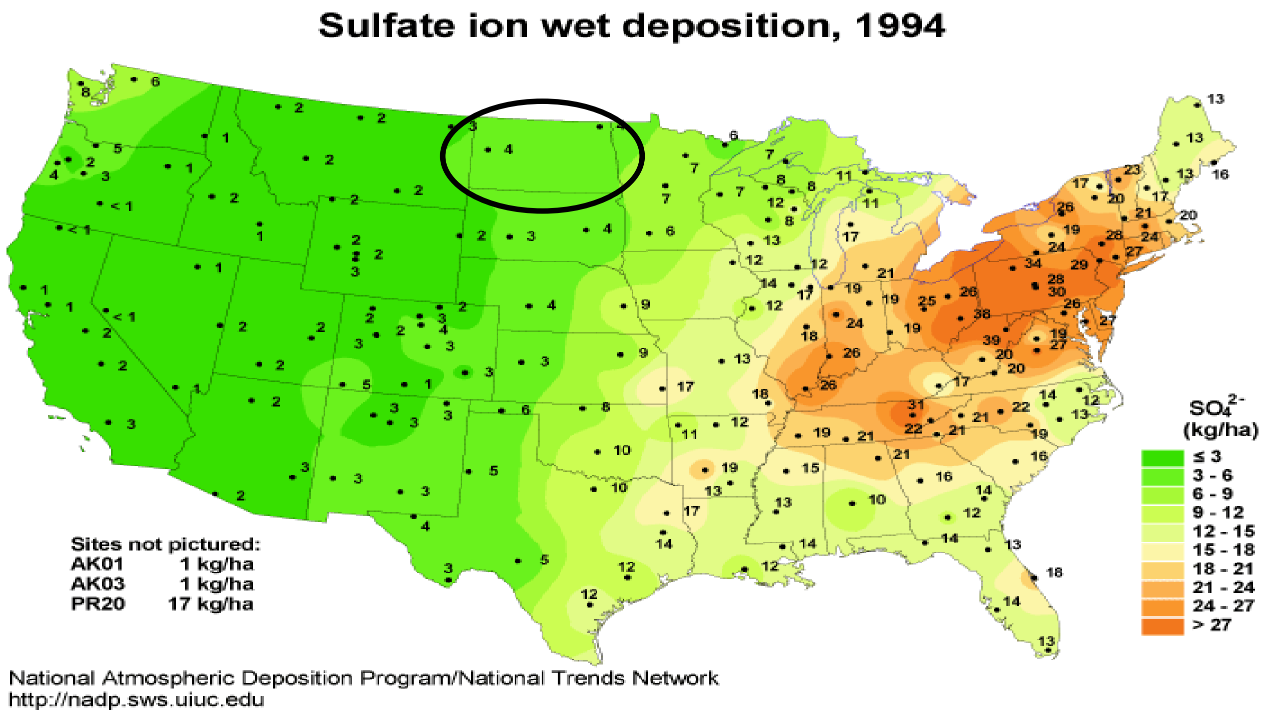

Fig. 50. Represents the amount of S in 1994 in North Dakota was 6-9 kg ha^{-1}.

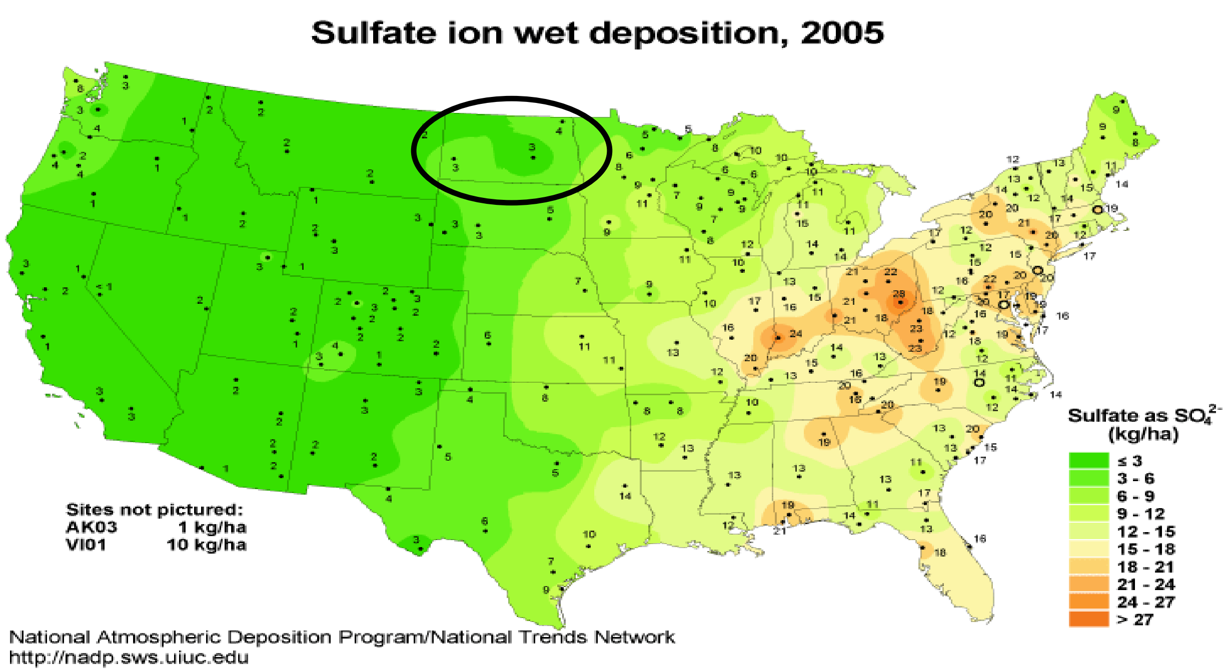

Fig. 51. Represents the amount of S in 2005 in North Dakota was 6-9 kg ha^{-1} with some parts in the range ≤3.

Sulfur deficiency resulted in a 50% reduction in chlorophyll *a* concentration in corn. Reduced chlorophyll *a* concentration resulted in decreased light absorbance and increased reflectance near 555 nm and 700 nm. Predicting S deficiency in soils is difficult due to the limitations of the S soil test in the North Dakota region Fig 53 (Franzen and Lukach 2013) such as S movment in soils, leaching ability especially in sandy textured soils, erosion, and spatial and temporal variations. Aerial imagery, satellite NDVI imagery, and ground based sensor NDVI measurement has been useful in qualitative assessment of crop health and chlorophyll status. Nutrient and water stress on plants can be detected using these rem0ote imager techniques, combined with ground truthing.

Nutrient deficiencies can be corrected with the application of fertilizers (Belay et al., 2002). The use of non-destructive sensors have been used to determine plant nutrient status (Ma et al., 1996; Solari et al., 2008; Mistele et al., 2008). Most of the sensor work has been devoted to crop N status (Wolfe et al., 1988). Due to differences in the properties of active-optical sensor wavelengths used in active optical sensors to predict the deficiency symptoms variety of indices have been developed to relate sensor readings for specific nutrient deficiencies. Several researchers have developed relationships for corn to determine N status (Ercoli et al., 1993; Blackmer et al., 1994).

Two ground-based active-optical sensors, GS and CC, readings using different wavelengths were used to detect the sulfur deficiencies. However, it is hard for sensor to detect the specific deficiency of particular nutrient because different stress can cause damage to the same pigment. Therefore, it is logical to standardize the sensors to detect the specific nutrient deficiency symptoms in crops.

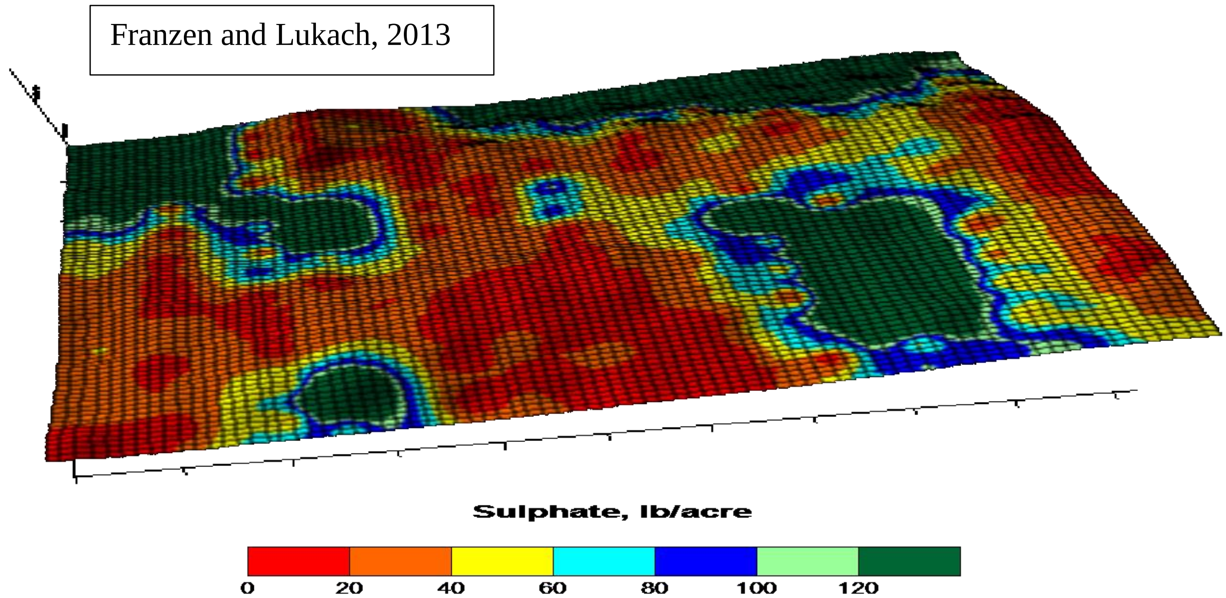

Fig. 52. Variation of Apparent soil sulfate (from ¼ acre grid sampling) in a 40 acre field in North Dakota.

The objective this study was to test whether GBAO sensors could distinguish N deficiency from S deficiency, and determine which of two wavelength indices was more efficient for identifying S deficiency using an N rich area within the field

7.3. Material and Methods

7.3.1. Locations

Two sites were selected for N rate trials in North Dakota during 2013 (Table 16). The sites were established within larger farm fields with the permission of the farmer cooperators. The farm cooperators were a mix of cooperators with whom NDSU researchers had worked with before, farmers recommended by Extension county agents and farmers who volunteered usually after winter meetings discussing the project. No supplement N, except for a small amount applied in furrow with the starter fertilizer application was applied by cooperator at all sites. The grower planted a corn hybrid of their choice, and applied herbicide at their discretion.

Table 16. Tillage system, soil type, planting date and date of the first and second sensing of experimental sites.

Locations	Tillage System	GPS Coordinated	Soil Type†	Planting Dates	First Sensing (V6 stage)	Second Sensing (V12 stage)
Arthur	Eastern medium-textured conventional-till sites	47° 06' 50.963" N, 97° 57' 55.219" W	Coarse-silty, mixed, superactive, frigid Pachic Hapludolls	05/15/13	06/20/13	07/10/13
Oakes	Eastern no-till site	46°06'38.066''N 97°57'55.219''	Coarse-silty, mixed, superactive, frigid Aeric Calciaquolls	05/11/13	06/18/13	07/09/13

† information collected from Soil Survey Staff, 2013.

The experimental design at each site was a randomized complete block with four replications and six treatments: check (no added N), 45, 90, 134, 179, and 224 kg N ha^{-1}. The N was applied as ammonium nitrate by hand within a week of planting. The S deficiency symptoms were appeared on the leaves (visually) at V6 growth stage, probably as a result of preplant excessive rainfall and their sandy loam texture, therefore gypsum at 22 kg ha^{-1} S (112 kg ha^{-1} gypsum) was applied as granules broadcast over the top of the corn to check the difference in readings before and after S deficiency correction. Each experimental unit (plot) was 6.1-m in length and 3.05-m in width.

7.3.2. Soil sampling

Five soil sample cores were collected from each experimental site before the start of field work using a 2.5-cm diameter hand probe to a depth of 0-15 cm for phosphorous (P), potassium (K), zinc (Zn), pH, and organic matter. Three soil cores to a depth of 0-60 cm were obtained for residual nitrate analysis. Soil sulfate was not determined on any soil sample, since the S soil analysis is not considered diagnostic in North Dakota and its use is discouraged. Collected soil samples were air-dried, ground to pass through a 2 mm screen, and thoroughly mixed before analysis for soil pH, available P, K, Zn, nitrate-nitrogen, and organic matter. Soil pH was analyzed using a 1:1 soil: deionized H_2O solution method (Watson and Brown, 1998); P by the Olsen method (Olsen et al., 1954b), potassium using the 1-N ammonium acetate method (Thomas, 1982). The DTPA extraction method (Lindsay and Norvell, 1978) coupled with atomic absorption spectroscopy detection was used for determination of available Zn. Organic matter was measured using the loss following ignition method (Schulte and Hopkins, 1996).

Fertilizer P and K were applied by the researchers if P and K application was not possible by the grower and if soil analysis found a need for its application. Phosphate was applied if needed as mono ammonium phosphate (11-52-0) and K as potassium chloride (0-0-60) at rates consistent with soil analysis based recommendations (Franzen, 2010). If the site was found to be Zn deficient, with DTPA extracted Zn levels below 0.8 ppm, the researchers applied zinc sulfate (36% granules) at a rate of 11 kg ha^{-1} Zn per acre as a broadcast the day of N treatment application. For the two sites that were suspected of being S deficient at V6, an application of gypsum at 22 kg ha^{-1} S (112 kg ha^{-1} gypsum) was applied as granules broadcast over the top of the corn. Both S deficient sites received at least 1.25 cm rainfall within a day of application.

7.3.3. Sensor description and sensing procedure

The formula for NDVI and red-edge NDVI follows as in eq 1:

$$red\ NDVI = (NIR - Red)/(NIR + Red)$$

$$Red\ Edge\ NDVI = (NIR - Red\ Edge)/(NIR + Red\ Edge)$$

Values of wavelengths we used for GS and CC sensor are defined below:

The GS emits two bands: red 656nm and near infrared 774nm. From equation 1:

$$\text{Red NDVI} = (774\text{nm} - 656\text{nm})/(774\text{nm} + 656\text{nm})$$

CC_ACS-470 emits three bands: red (670nm), red-edge (730nm), and near infrared (760nm): Fill these values in equation 1:

$$\text{Red NDVI} = (760\text{nm} - 670\text{nm})/(760\text{nm} + 670\text{nm})$$

For red-edge value, fill the numbers in equation 2:

$$\text{Red-edge NDVI} = (760\text{nm} - 730\text{nm})/(760\text{nm} + 730\text{nm})$$

The GS and CC readings were collected at V6 stage and again about 10 days to 2 weeks later when the corn reached the V12 stage. Readings were taken over the top of the corn canopy. All reflectance data were inserted within the generalized NDVI expression:

(NIR – Red or Red-edge) / (NIR+ Red or Red-edge)

The red-edge wavelength measurement differs from the red NDVI measurement because the red-edge measures plant chlorophyll content (Horler et al. 1983). The GS and CC readings consisted of a mean of between 30 and 50 individual readings from each plot. Means of sensor readings within a treatment were determined using excel macro program for GS and CC raw data (Franzen 2012). To calculate INSEY, the sensor reading is divided by the growing degree days from the date of planting. (Raun et al. 2001) values were used to calculate the relationship between the N rate and sensor readings.

7.3.4. Statistical analysis

Quadratic regression analyses were conducted on N rate as the independent variable and sensor readings as the dependent variable at V6 and V12. The determination coefficient (r^2) value was used to evaluate the relationship of N rate and sensor reading. The SAS procedure PROC REG for Windows V9.2 (SAS Institute, Cary, NC) was used to calculate the r^2 of the quadratic model.

SAS GLM was used to compare the N treatments. P-value of 5% probability was used to differentiate treatments.

7.4. Results

At Arthur, readings from all the wavelengths tended to be lower with supplemental N at V6 just prior to S application, while readings were higher at V12 following S application (Figs. 53 to 60 and 75 to 82). The CC red-edge INSEY was similar as CC red INSEY at V6 (Fig. 53 and Fig. 54) in detecting lower readings with increased N rate, and CC red and red-edge INSEY were similar at V12 (Fig. 55 and Fig. 56) when S deficiency had been corrected. Similar results were observed with the GS (Figs. 57 to 60 and 79 to 82). The GS red-edge INSEY relationship was comparatively stronger (Fig. 75 and Fig. 80) than the CC red-edge INSEY at V6, while the CC red-edge and red INSEY with yield (Fig. 77 and 78) tended to be slightly greater at V12 compared to the GS red-edge and red INSEY (Fig. 82 and 83). At V6, there was little relationship between readings and plant height. However, after S application at V12, plant height increased with N application (Figs. 61 and 62). Yield at Arthur increased with increasing N rate (Fig. 63).

At Oakes, the CC readings tended to decrease with N rate at V6 (Figs. 64 and 65) while GS readings detected little difference between N treatments at V6 (Figs. 67 and 68). At V12, the CC readings and GS readings increased with N rate (Figs. 66 and 67, and Figs. 70 and 71). Plant height was not affected by N rate at V6 at Oakes, however, plant height increased with N rate at V12. Corn yield was not affected by N rate at Oakes, probably due to very dry conditions from July 1 through the remaining growing season.

Regression analysis at Oakes using the CC resulted in a slight decrease in readings with N rate using red and red-edge INSEY at V6, while readings increased with N rate at V12 (Figs. 83 to 84). Analysis at Oakes using the GS provided similar results as the CC (Figs. 87 to 88).

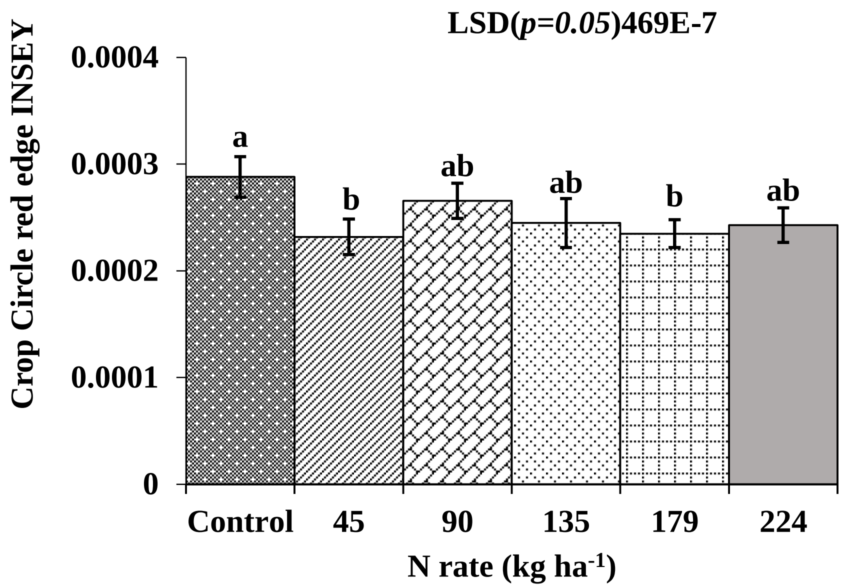

Fig. 53. Relationship between N rate and Crop circle red-edge INSEY (Crop circle red-edge wavelength reading/growing degree-days), V6 at Arthur.

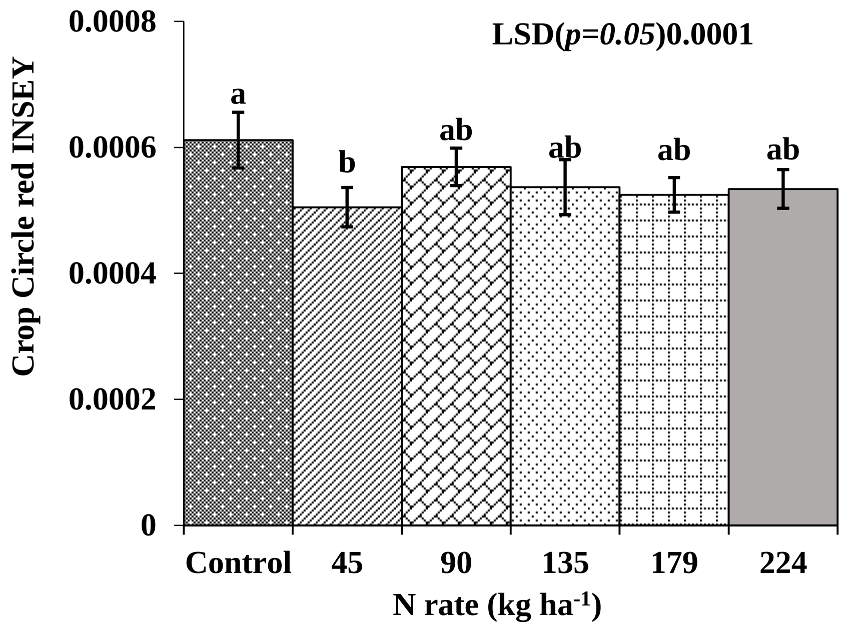

Fig. 54. Relationship between N rate and Crop circle red INSEY (Crop circle red wavelength reading/growing degree-days), V6 at Arthur.

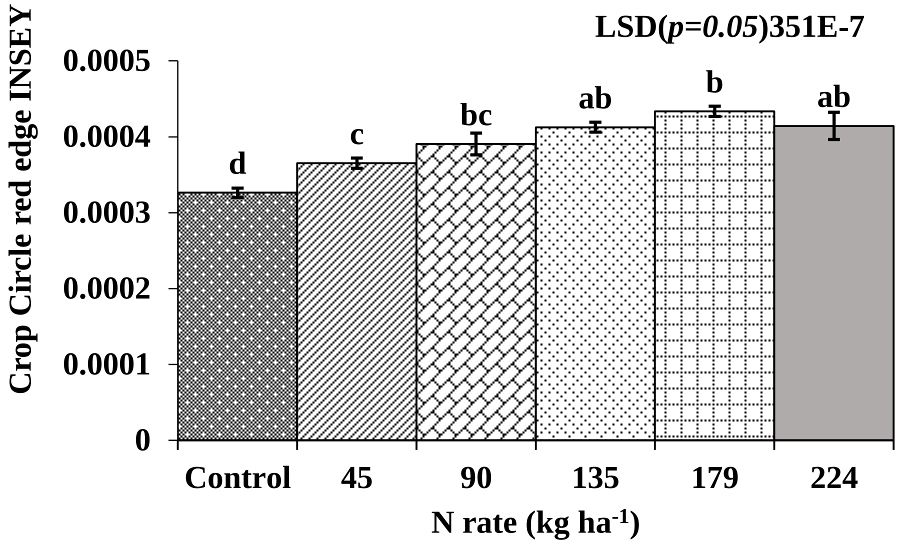

Fig. 55. Relationship between N rate and Crop circle red-edge INSEY (Crop circle red-edge wavelength reading/growing degree-days), V12 at Arthur.

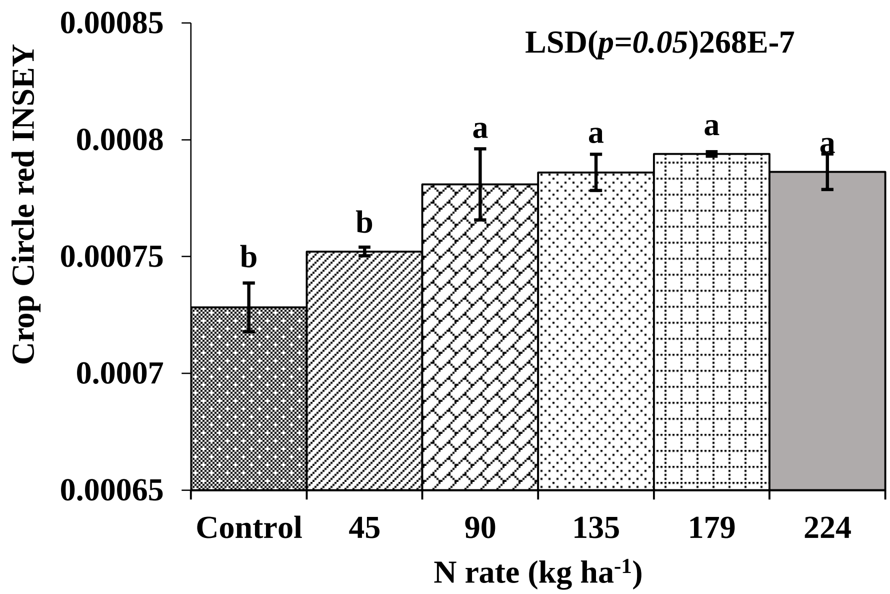

Fig. 56. Relationship between N rate and Crop circle red INSEY (Crop Circle red wavelength reading/growing degree-days), V12 at Arthur.

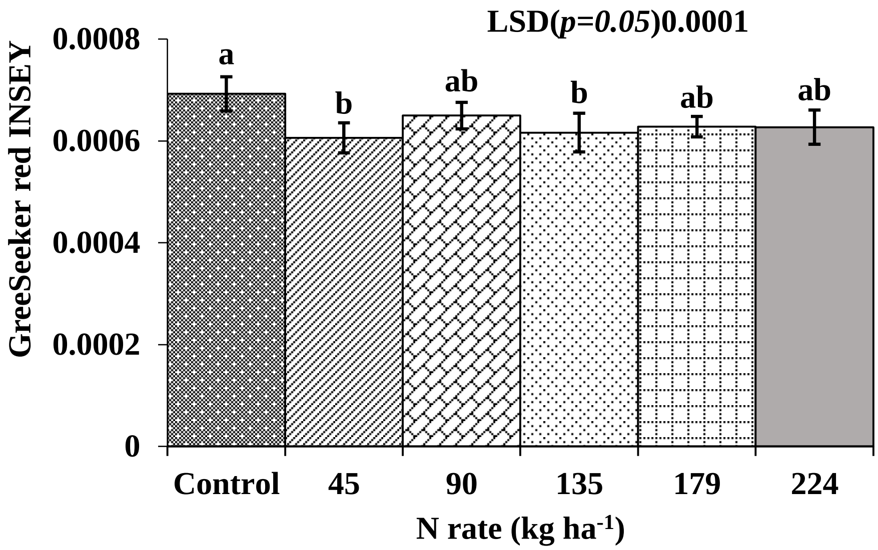

Fig. 57. Relationship between N rate and GreenSeeker red INSEY (GreenSeeker red wavelength reading/growing degree-days), V6 at Arthur.

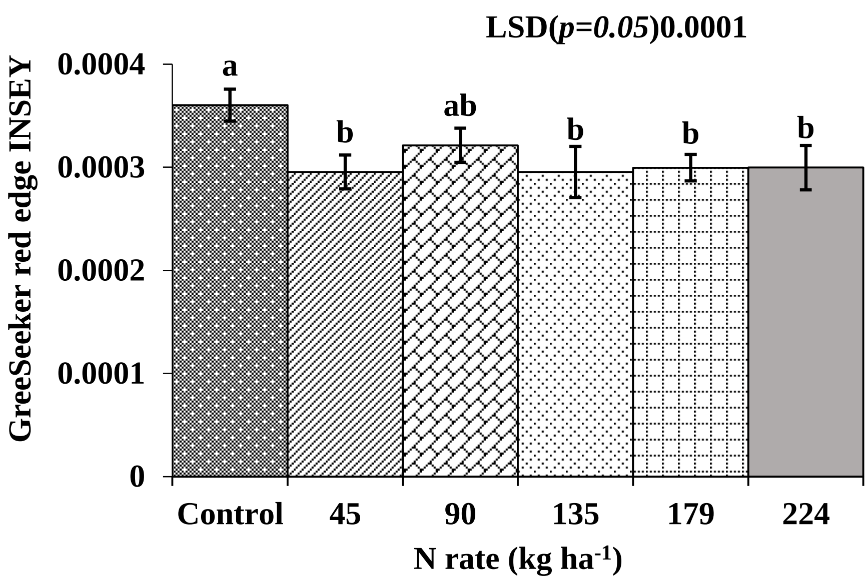

Fig. 58. Relationship between N rate and GreenSeeker red-edge INSEY (GreenSeeker red-edge wavelength reading/growing degree-days), V6 at Arthur.

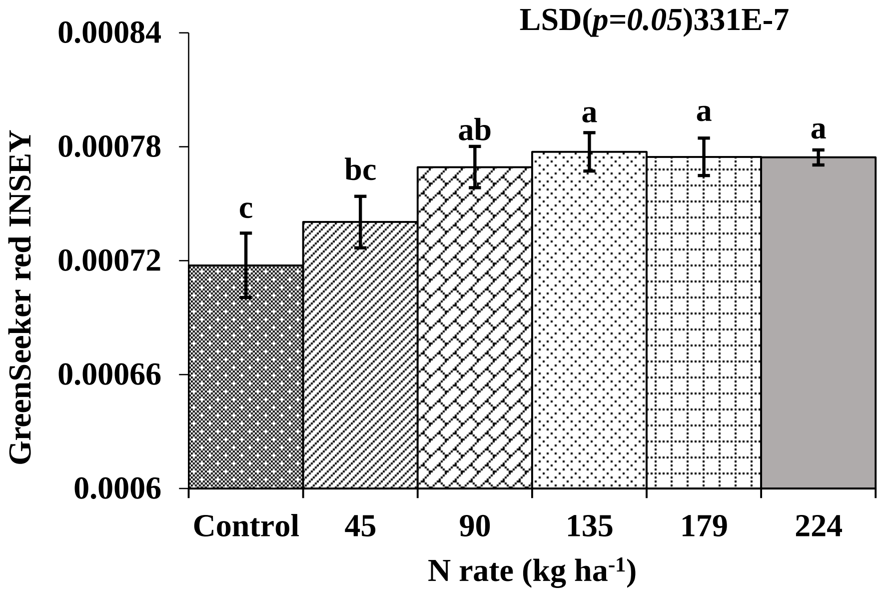

Fig. 59. Relationship between N rate and GreenSeeker red INSEY (GreenSeeker red wavelength reading/growing degree-days), V12 at Arthur.

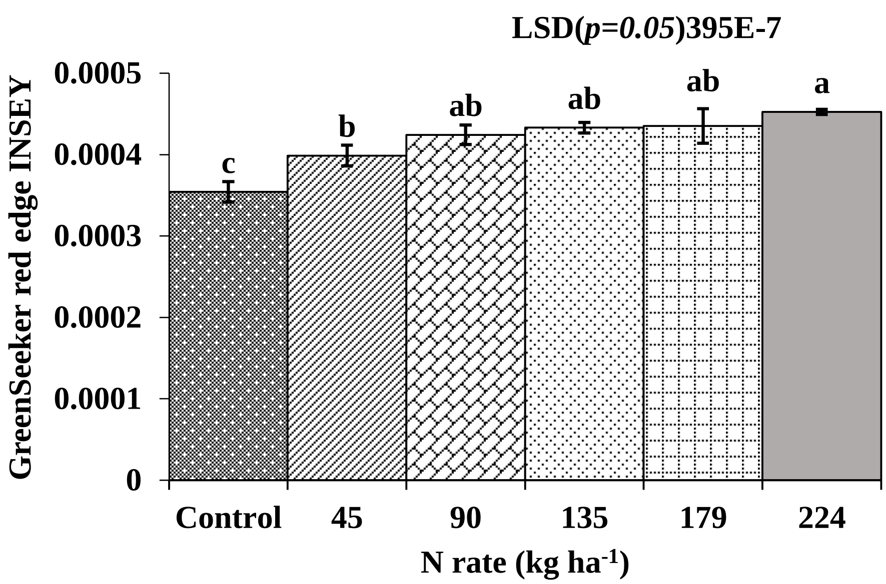

Fig. 60. Relationship between N rate and GreenSeeker red-edge INSEY (GreenSeeker red-edge wavelength reading/growing degree-days), V12 at Arthur.

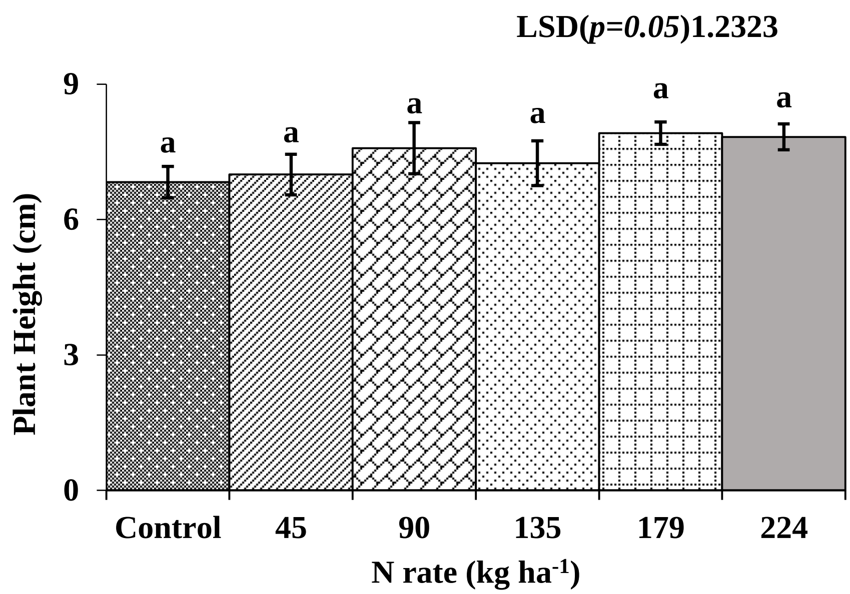

Fig. 61. Relationship between N rate and plant height, V6 at Arthur.

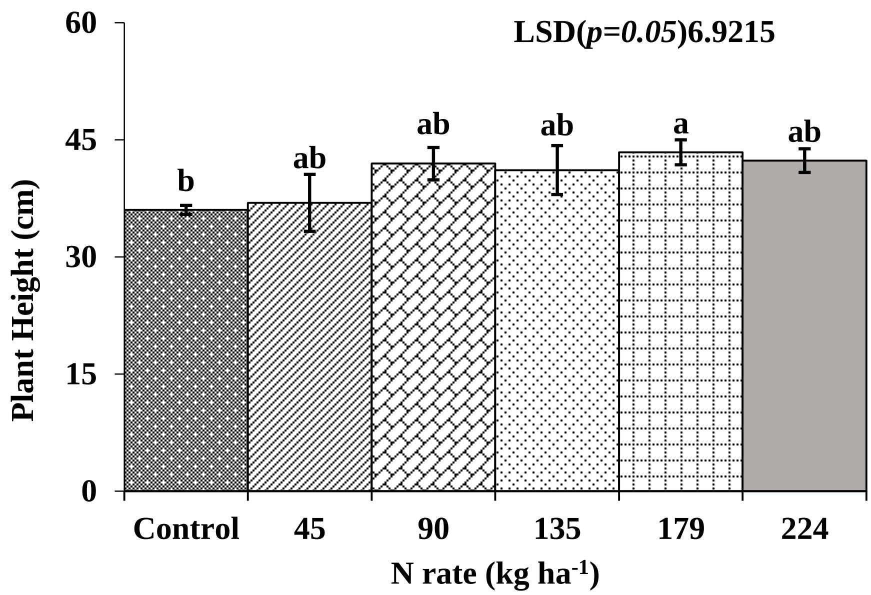

Fig. 62. Relationship between N rate and plant height, V12 at Arthur.

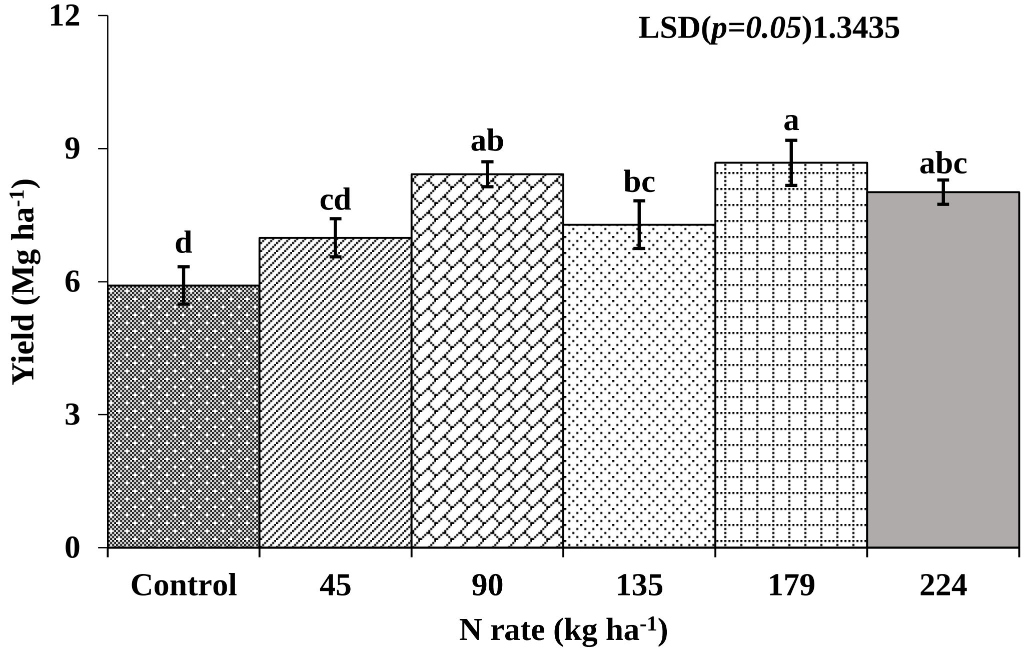

Fig. 63. Relationship between N rate and corn yield at Arthur.

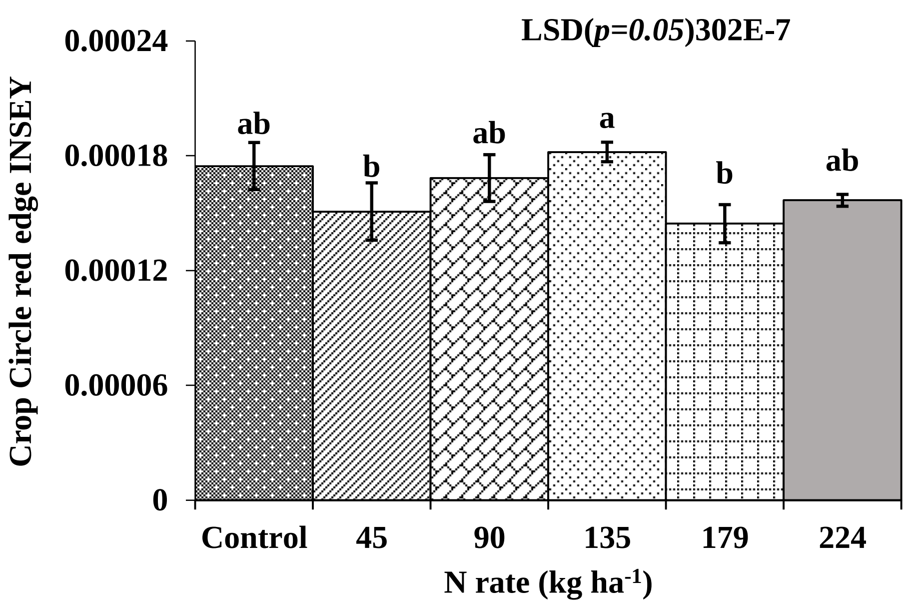

Fig. 64. Relationship between N rate and Crop Circle red-edge INSEY (Crop Circle red-edge wavelength reading/growing degree days), V6 at Oakes.

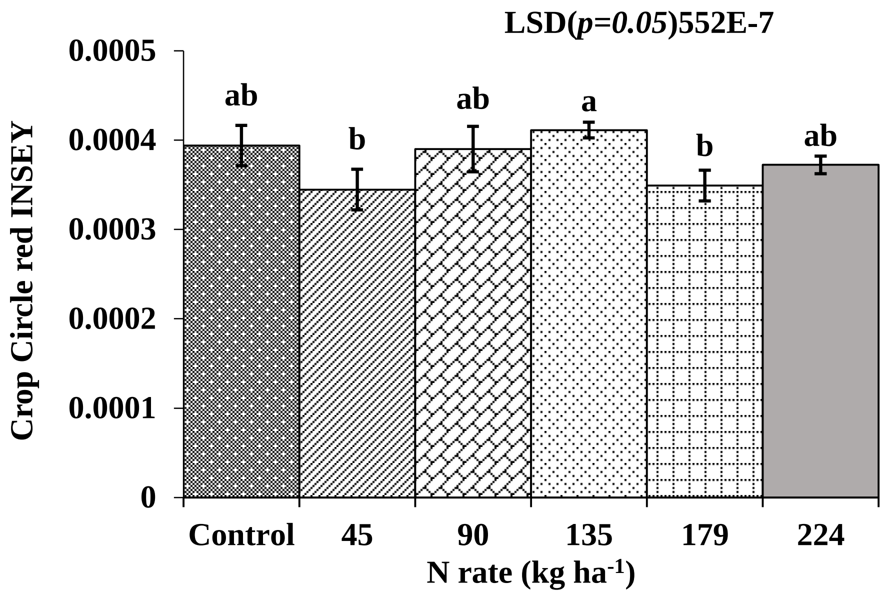

Fig. 65. Relationship between N rate and Crop Circle red INSEY (Crop Circle red wavelength reading/growing degree days), V6 at Oakes.

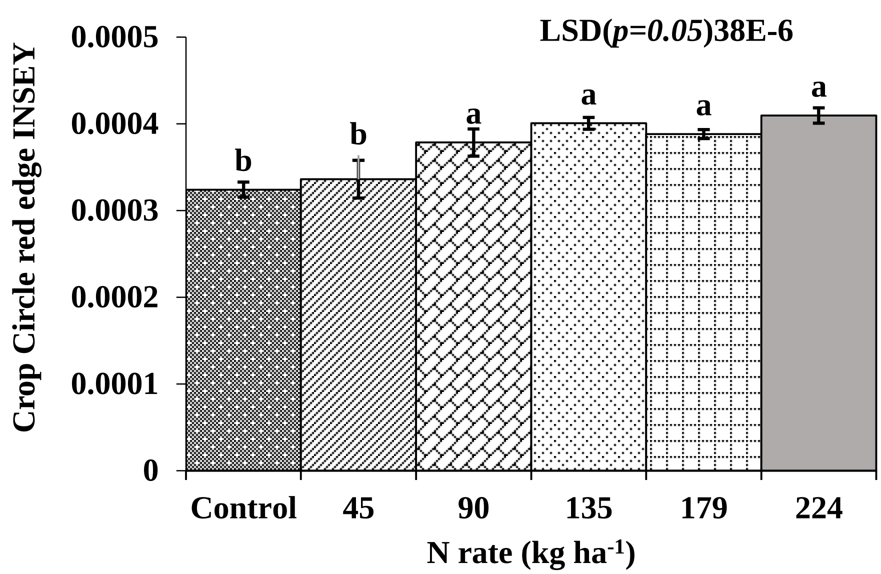

Fig. 66. Relationship between N rate and Crop Circle red-edge INSEY (Crop Circle red-edge wavelength reading/growing degree days), V12 at Oakes.

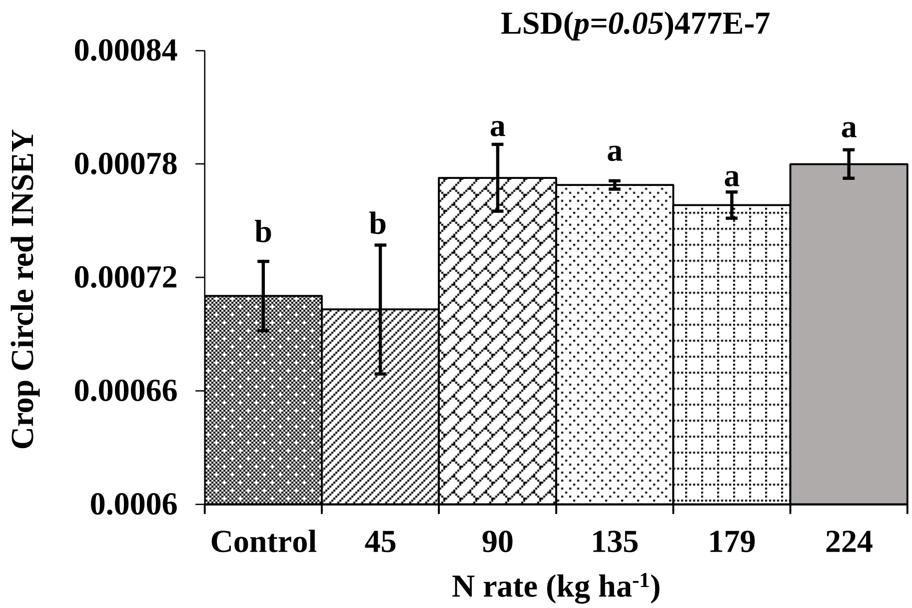

Fig. 67. Relationship between N rate and Crop Circle red INSEY (Crop Circle red wavelength reading/growing degree-days), V12 at Oakes.

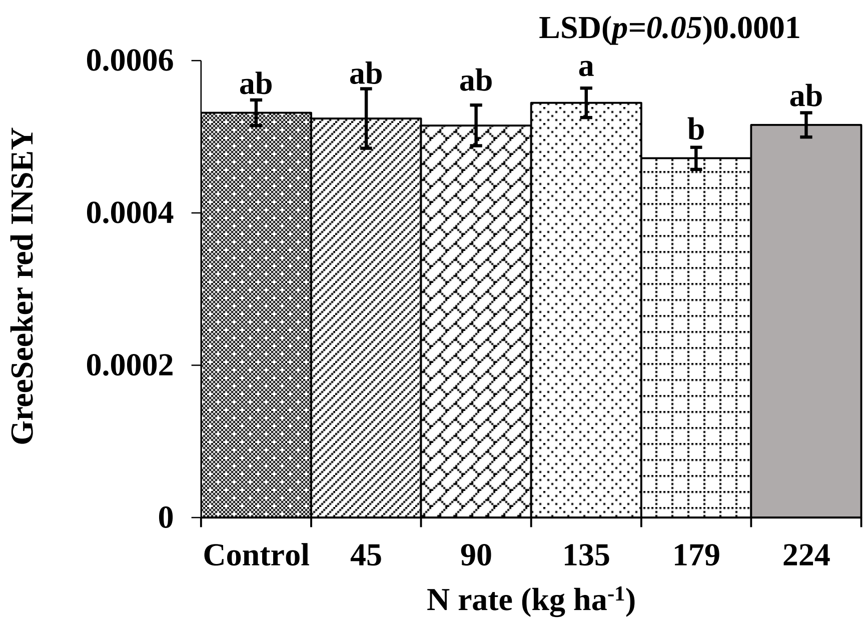

Fig. 68. Relationship between N rate and GreenSeeker red INSEY (GreenSeeker red wavelength reading/growing degree-days), V6 at Oakes.

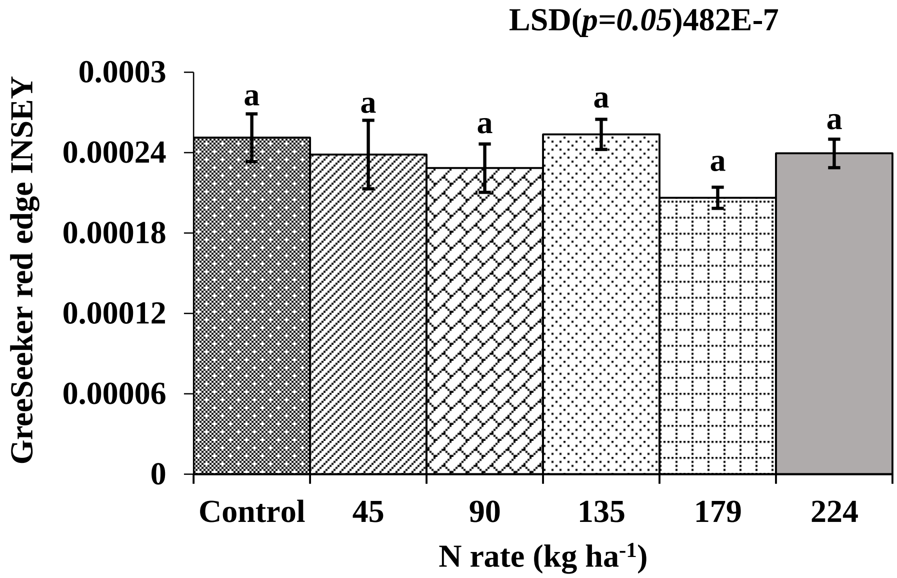

Fig. 69. Relationship between N rate and GreenSeeker red-edge INSEY (GreenSeeker red-edge wavelength reading/growing degree-days), V6 at Oakes.

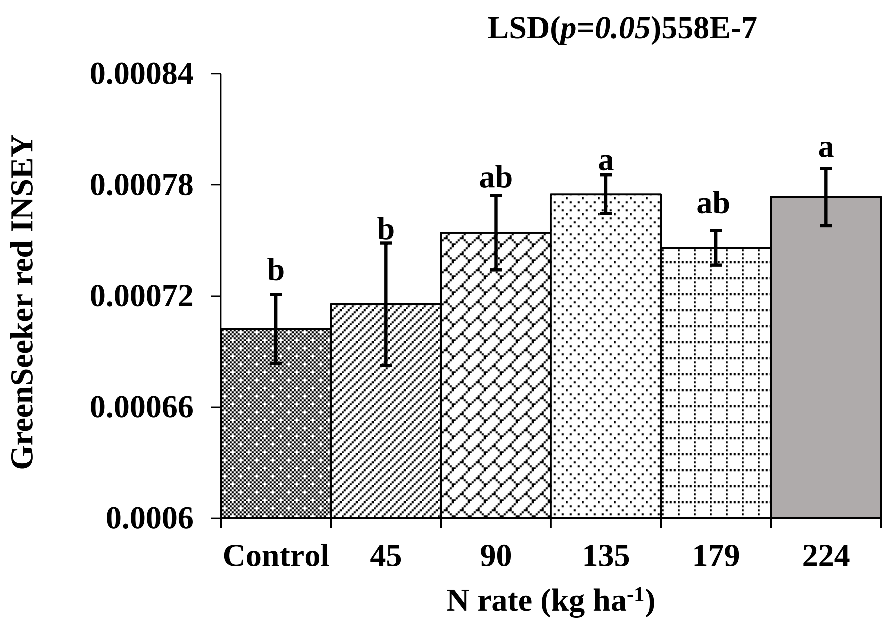

Fig. 70. Relationship between N rate and GreenSeeker red INSEY (GreenSeeker red wavelength reading/growing degree-days), V12 at Oakes.

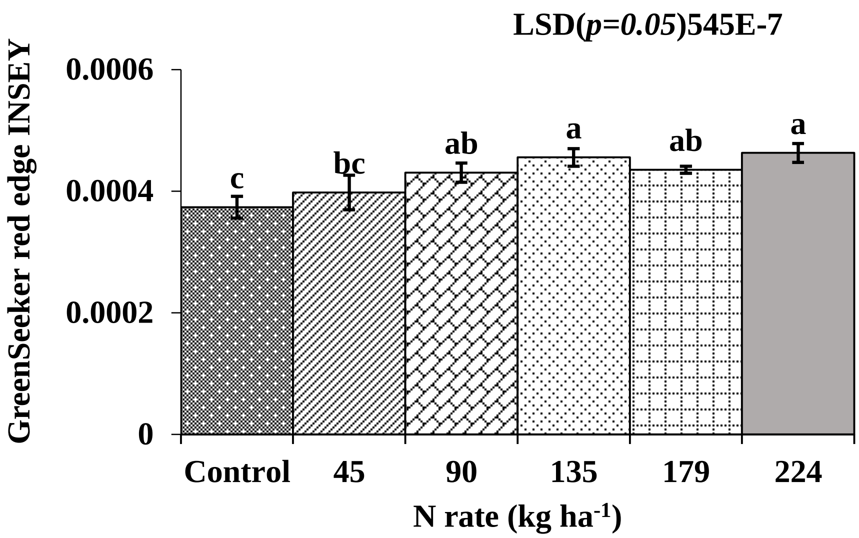

Fig. 71. Relationship between N rate and GreenSeeker red-edge INSEY (GreenSeeker red-edge wavelength reading/growing degree-days), V12 at Oakes.

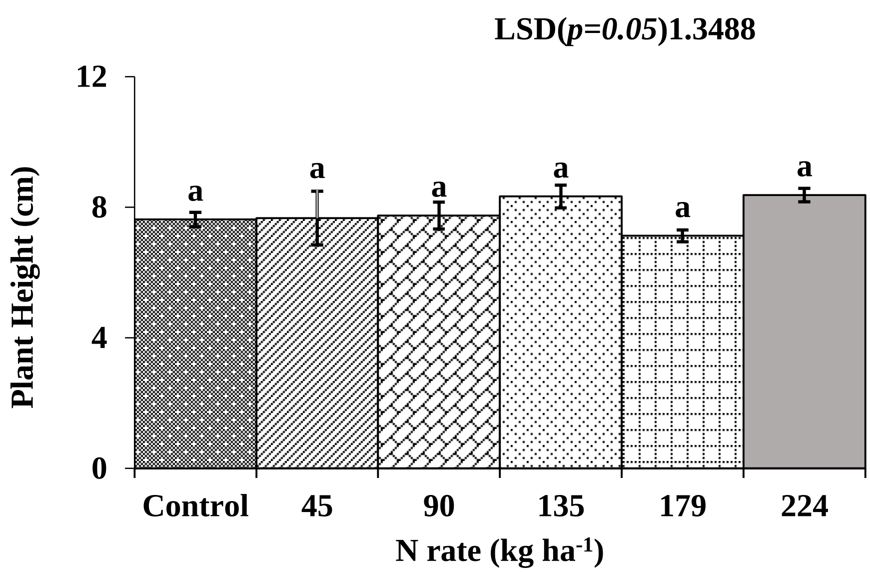

Fig. 72. Relationship between N rate and plant height at V6 at Oakes.

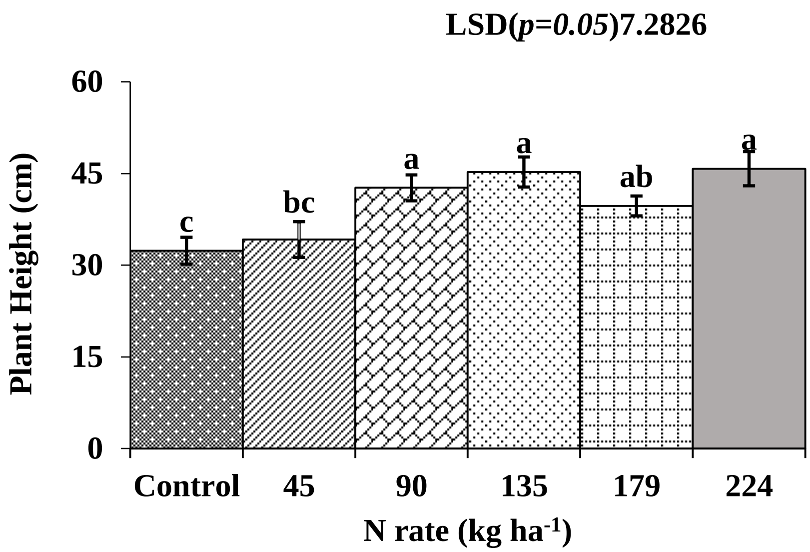

Fig. 73. Relationship between N rate and plant height at V12 at Oakes.

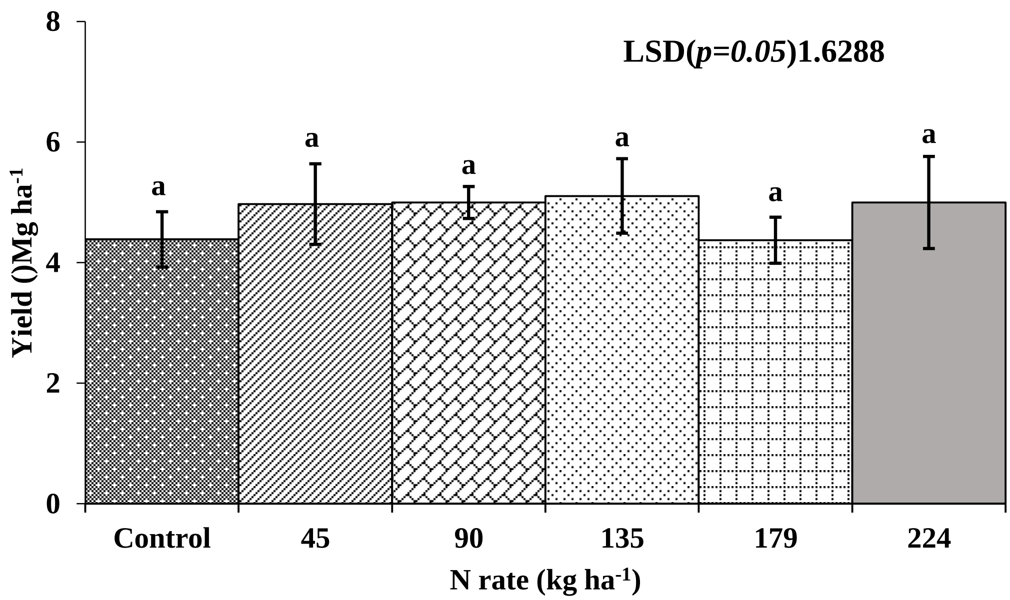

Fig. 74. Relationship between N rate and corn yield at Oakes.

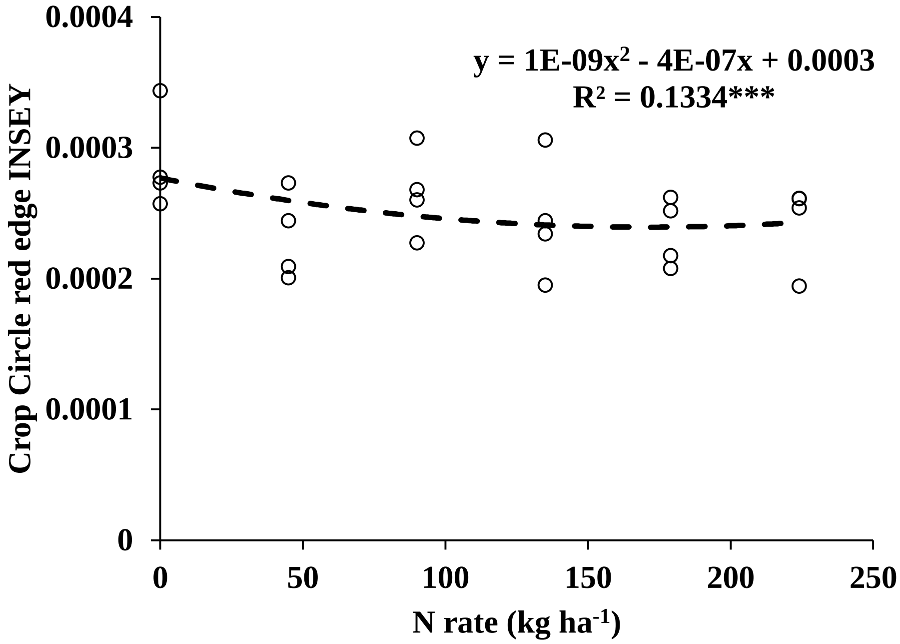

Fig. 75. Relationship of Crop Circle red-edge INSEY (sensor red-edge NDVI/growing degree-days from planting to sensing) and N rate, V6 stage at Arthur. †* denotes significance at 0.001.**

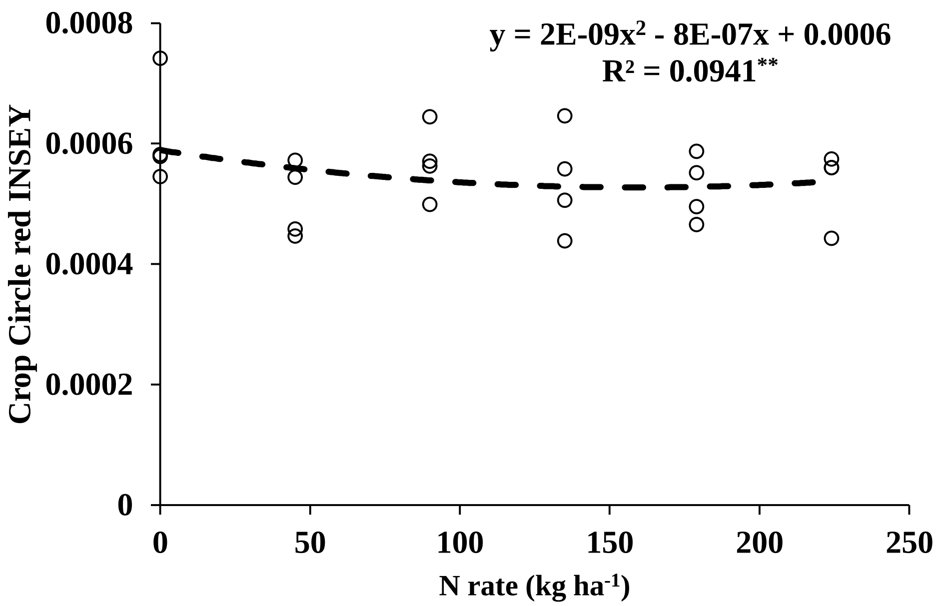

Fig. 76. Relationship of Crop Circle red INSEY (sensor red NDVI/growing degree-days from planting to sensing) and N rate, V6 stage at Arthur. † denotes significance at 0.01.**

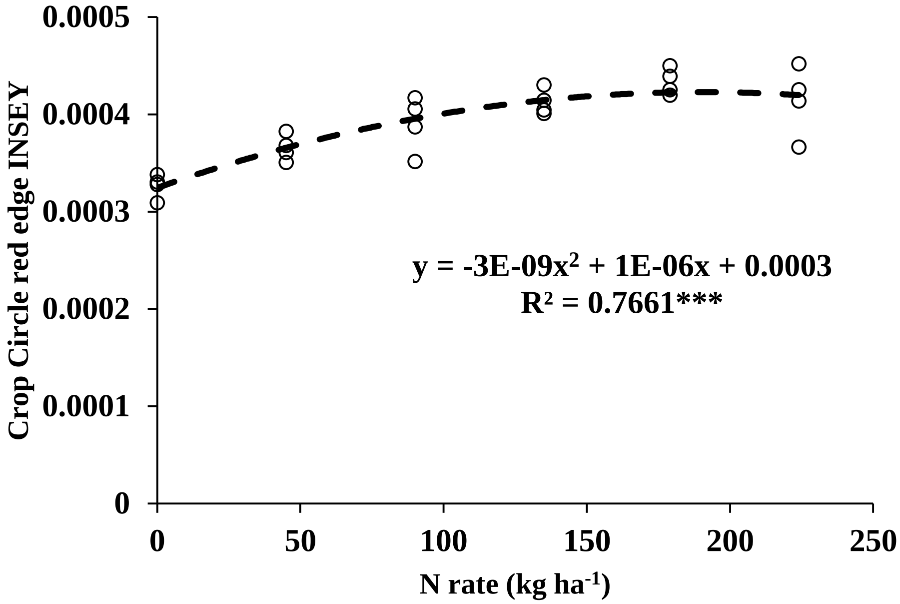

Fig. 77. Relationship of Crop Circle red-edge INSEY (sensor red-edge NDVI/growing degree-days from planting to sensing) and N rate, V12 stage at Arthur. †* denotes significance at 0.001.**

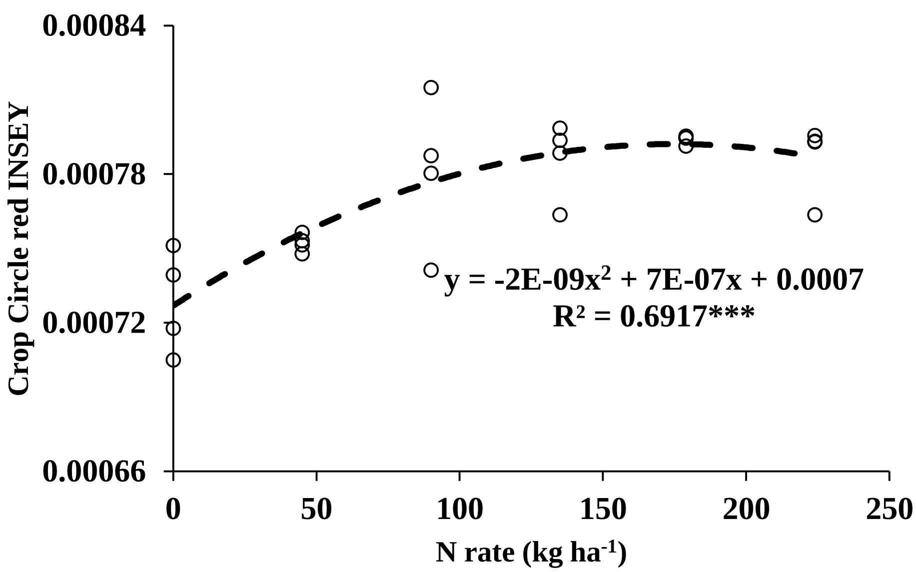

Fig. 78. Relationship of Crop Circle red INSEY (sensor red NDVI/growing degree-days from planting to sensing) and N rate, V12 at Arthur. †* denotes significance at 0.001.**

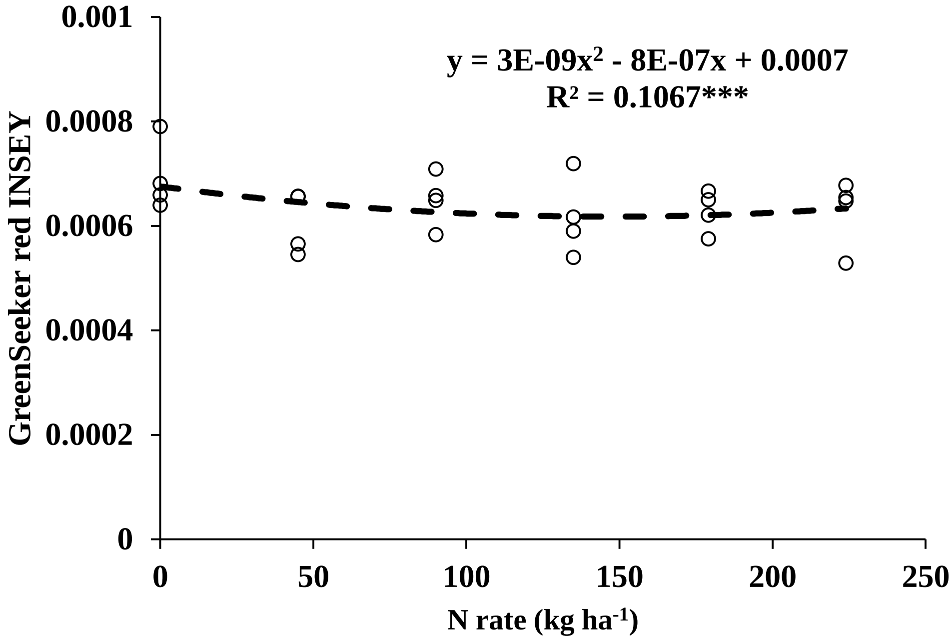

Fig. 79. Relationship of GreenSeeker red INSEY (sensor red NDVI/growing degree-days from planting to sensing) and N rate, V6 at Arthur. † denotes significance at 0.01.**

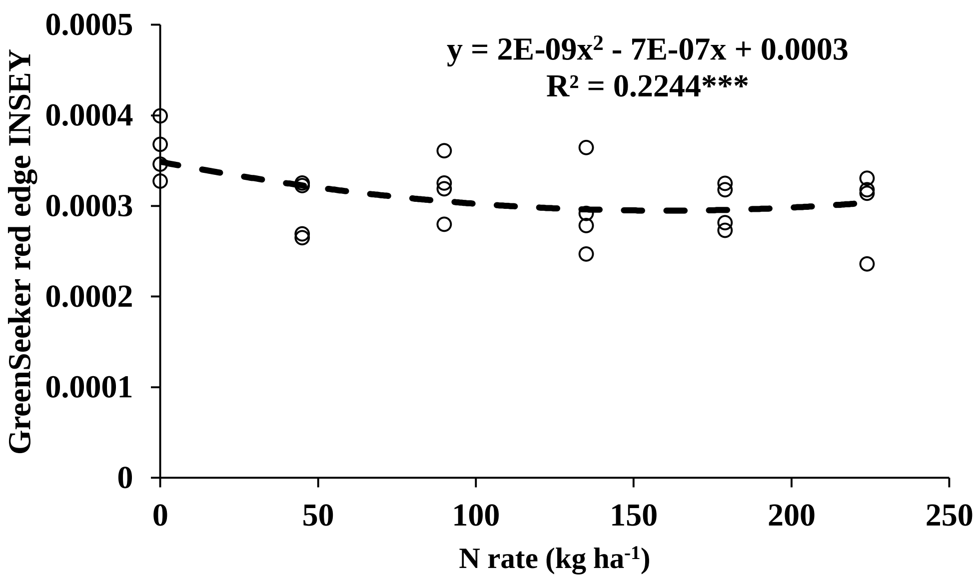

Fig. 80. Relationship of GreenSeeker red-edge INSEY (sensor red-edge NDVI/growing degree-days from planting to sensing) and N rate, V6 at Arthur. †* denotes significance at 0.001.**

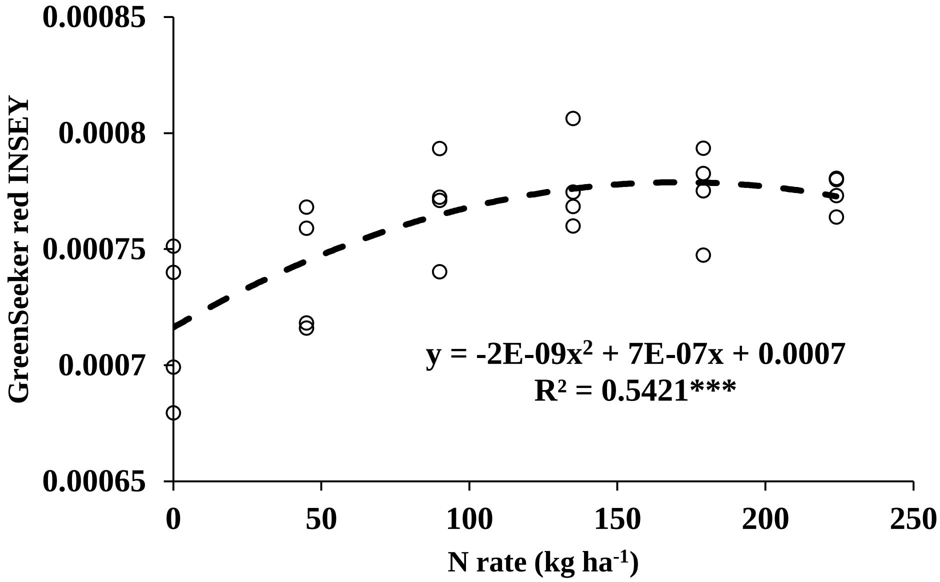

Fig. 81. Relationship of GreenSeeker red INSEY (sensor red NDVI/growing degree-days from planting to sensing) and N rate, V12 at Arthur. †* denotes significance at 0.001.**

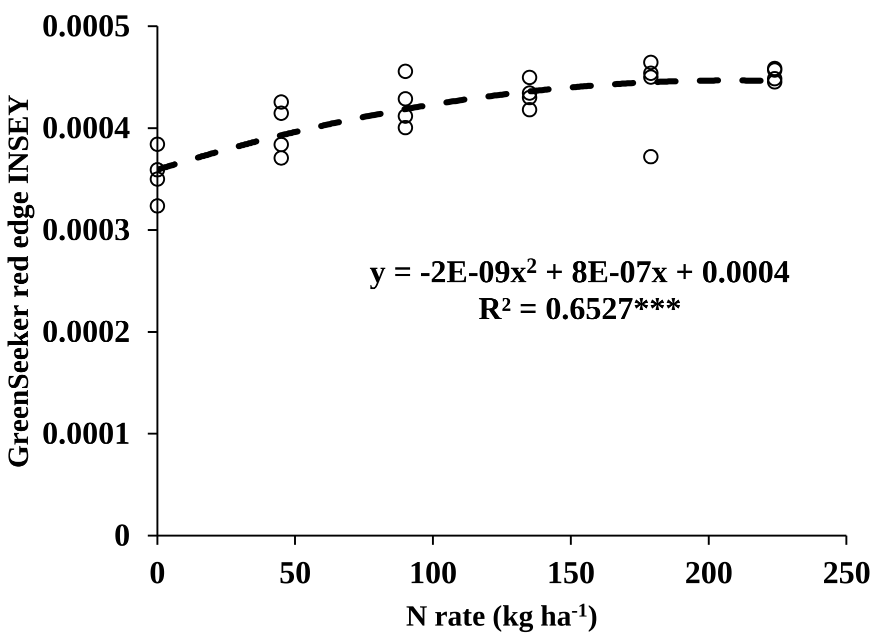

Fig. 82. Relationship of GreenSeeker red-edge INSEY (sensor red-edge NDVI/growing degree-days from planting to sensing) and N rate, V12 at Arthur. †* denotes significance at 0.001.**

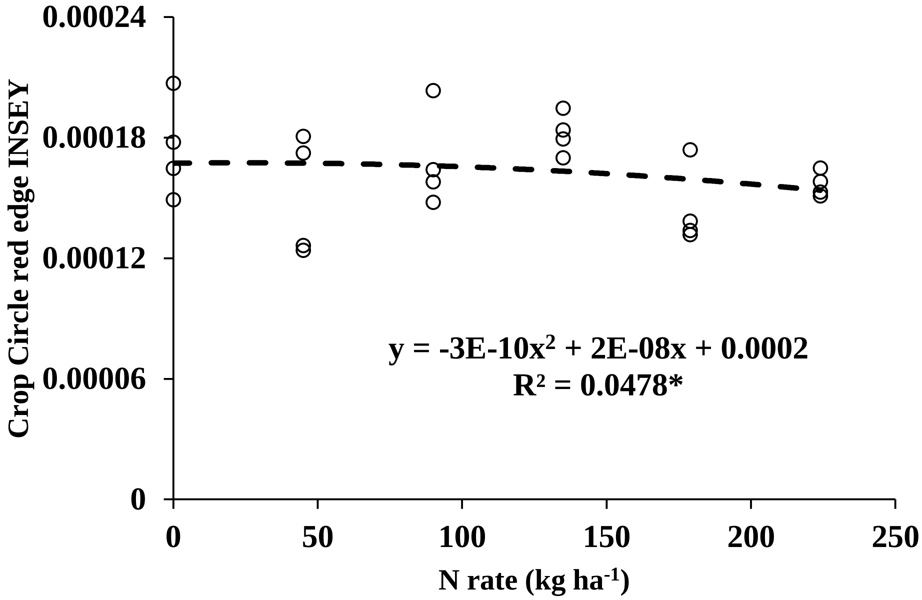

Fig. 83. Relationship of Crop Circle red-edge INSEY (sensor red-edge NDVI/growing degree-days from planting to sensing) and N rate, V6 at Oakes. †* denotes significance at 0.05.

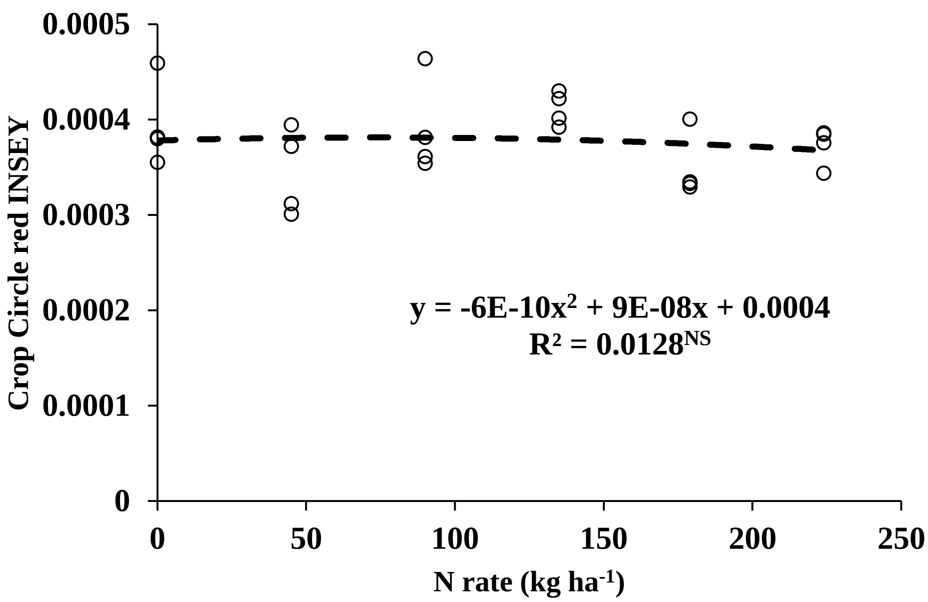

Fig. 84. Relationship of Crop Circle red INSEY (sensor red NDVI/growing degree-days from planting to sensing) and N rate, V6 at Oakes.

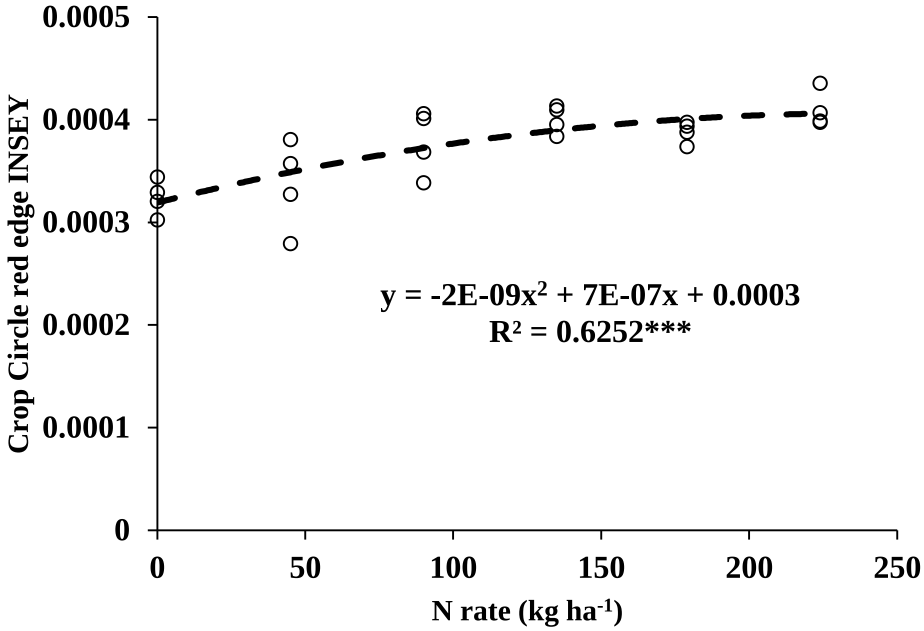

Fig. 85. Relationship of Crop Circle red-edge INSEY (sensor red-edge NDVI/growing degree-days from planting to sensing) and N rate, V12 at Oakes. †* denotes significance at 0.001.**

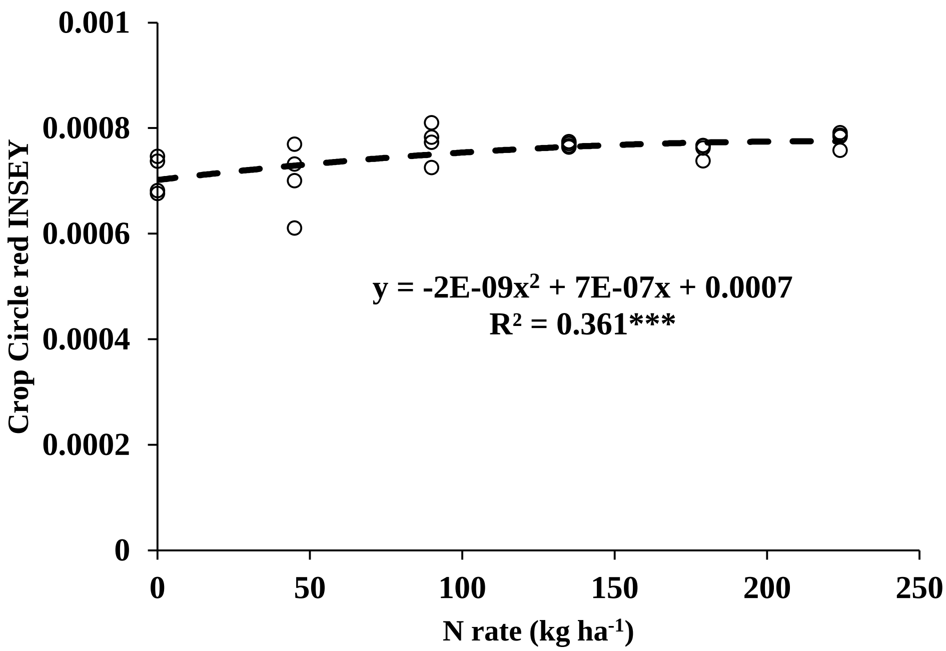

Fig. 86. Relationship of Crop Circle red INSEY (sensor red NDVI/growing degree-days from planting to sensing) and N rate, V12 at Oakes. †* denotes significance at 0.001.**

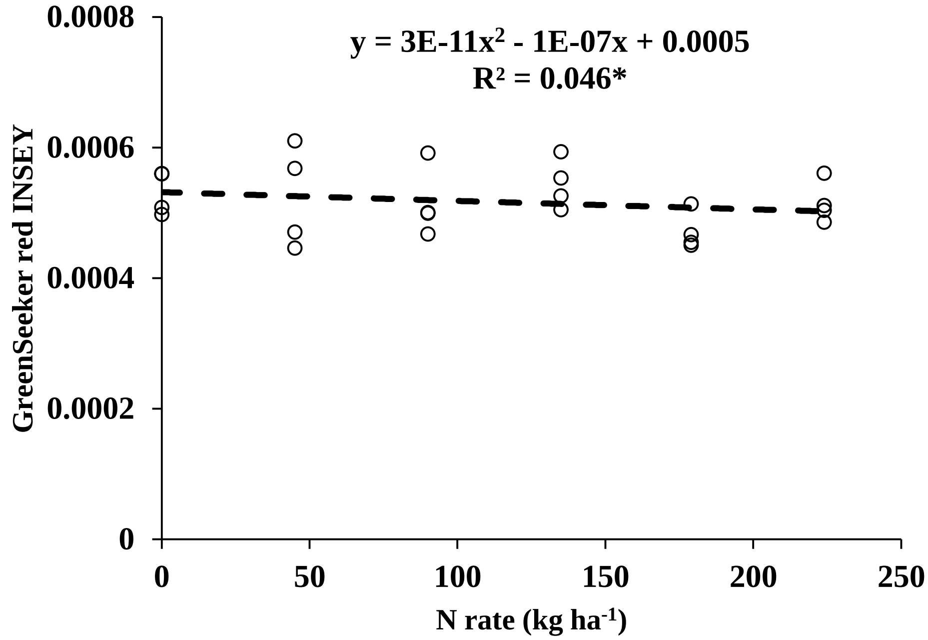

Fig. 87. Relationship of GreenSeeker red INSEY (sensor red NDVI/growing degree-days from planting to sensing) and N rate, V6 at Oakes. †* denotes significance at 0.05.

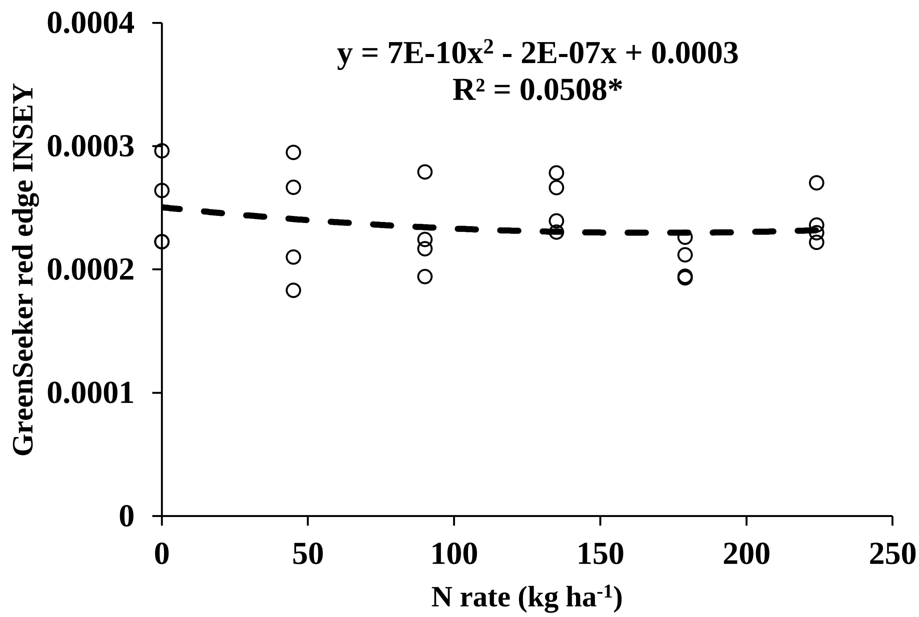

Fig. 88. Relationship of GreenSeeker red-edge INSEY (sensor red-edge NDVI/growing degree-days from planting to sensing) and N rate, V6 at Oakes. †* denotes significance at 0.05.

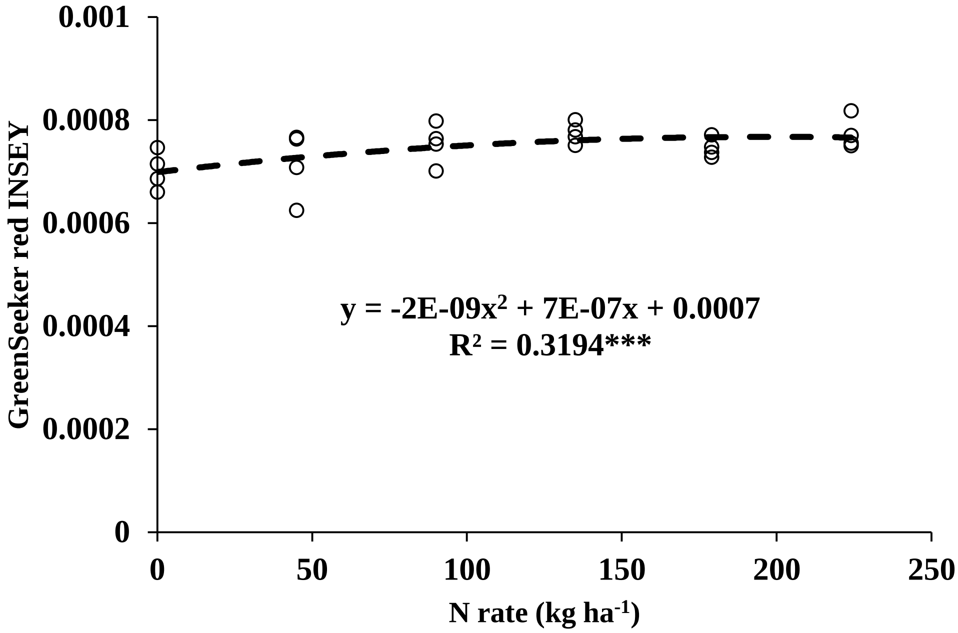

Fig. 89. Relationship of GreenSeeker red INSEY (sensor red NDVI/growing degree-days from planting to sensing) and N rate, V12 at Oakes. †* denotes significance at 0.001.**

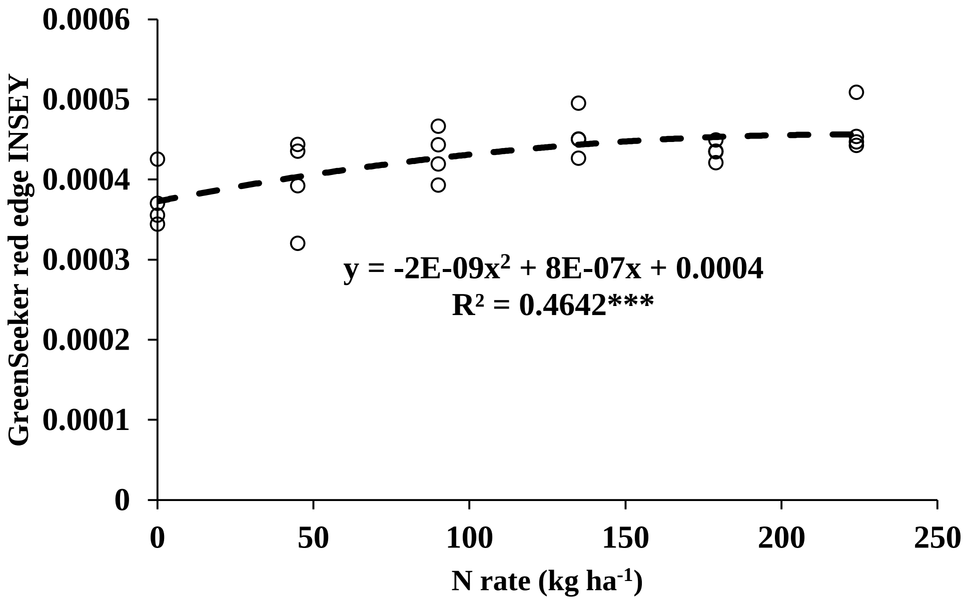

Fig. 90. Relationship of GreenSeeker red-edge INSEY (sensor red-edge NDVI/growing degree-days from planting to sensing) and N rate, V12 at Oakes. †* denotes significance at 0.001.**

7.5. Discussion

Sulfur deficiency has been shown to intensify with N fertilization (Mahli and Gill, 2006). In this study, N rate tended to decrease sensor readings at V6. Decreased sensor readings indicate that if S was not applied, lower yield would result with added N. Sulfur was applied within a day of V6 readings. Sensor readings at V12 increased with N rate at both sites, and at Arthur, N rate resulted in increased corn yield. Lower sensor readings at V6 might therefore be an indication of S deficiency that should be corrected before later sensor readings are used as a tool to help correct N deficiency.

Two sites responded differently to S deficiency and its correction in terms of yield because different soils require different amounts of fertilizer due to difference organic matter content and texture (Ridley 1972, 1973; Hamm et al. 1973; Harapiak 1980; Beaton and Soper1986; Doyle and Cowell 1993). Another reason of change in response to the S application might be due to the differences in corn cultivars (Wetter et al. 1970; Nuttall et al. 1987; Asare and Scarisbrick 1995).

The weak relationship between red INSEY and yield at V12 could be due to the higher LAI as result of gypsum application at V6 leaf stage. Similar results were reported by Ahmad et al. (1998), where he found increase in LAI, photosynthesis rate, and biomass accumulation in canola due to increase in S application. In addition, he observed that two canola cultivars (*B. juncea and B. rapa*) accumulated different biomass and photosynthesis rate, which resulted into different grain yield.

7.6. Conclusion

Significant differences in readings within the N rate treatment was observed both at V6 due to S deficiency. The readings were decreasing with increasing in N rate due to S deficiency at V6 growth stage. The CC was genrally better than GS in detecting S deficiency because regression coeffeicent determined with CC wavelength was better than GS wavelength. Plant height was found insignificant at V6 but after gypsum application, it was significant at V12 under both locations. The CC red-edge INSEY was similar as CC red INSEY at V6 in detecting lower readings with increased N rate, and CC red and red-edge INSEY were similar at V12 when S deficiency had been corrected. The differences in abilities of sensors to detect S deficiency was due to different range of red and red-edge INSEY were used in both the sensors.

7.7. Literature Cited

Adams, M.L., W.A. Norvell, J.H. Peverly, and W.O. Philpot. 1993. Fluorescence and reflectance characteristics of manganese deficient soybean leaves: effect of leaf age and choice of leaflet. Plant Soil. 156:235-238.

Ahmad, A., G. Abraham, N. Gandotra, and Y.P. Abrol. 1998. Interactive effect of nitrogen and sulphur on growth and yield of rapeseed-mustard (Brassica juncea L. Czern. And Coss. And Brassica campestris L.) genotypes. J. Agron. Crop Sci. 181:193–199.

Al-Abbas, A.H., R. Barr, J.D. Hall, F.L. Crane, and M.F. Baumagardner. 1974. Spectra of normal and nutrient-deficient maize leaves. Agron. J. 66:16-20.

Barker, A.V., and D.J. Pilbeam. 2007. Handbook of Plant Nutrition- Chapter 7 Sulfur. S. Haneklaus, E. Bloem, E. Schnug, L.J. de Kok, and I. Stulen. P. 183-225.

Beaton, J.D., and R.J. Soper. 1986. Plant response to sulphur in west-river Canada. Sulphur in agriculture, Monograph no. 27. SSSA, Madison, WI. Pp. 375–403.

Belay, A., A.S. Claassens, and F.C. Wehner. 2002. Effect of direct nitrogen and potassium and residual phosphorous fertilizers on soil chemical properties, microbial components and corn yield under long-term crop rotation. Biol. Fertil. Soils. 35:420-427.

Blackmer, T.M., J.S. Schepers, and G.E. Varvel. 1994. Light reflectance compared with other nitrogen stress measurements in corn leaves. Agron. J. 86 (6): 934-938.

Ercoli, L., M. Mariotti, A Masoni and F. Massantini. 1993. Relationship between nitrogen and chlorophyll content and spectral properties in maize leaves. European Journal ofAgronomy 2: II3-II7

Franzen, D. W. 2010. North Dakota fertilizer recommendation tables and equations. NDSU Extension Circular SF-882. North Dakota State University Extension Service, Fargo, ND.

Franzen, D.W. and J. Lukach. 2013. Fertilizing canola and mustard. NDSU Extension Circular SF-122. North Dakota State University Extension Service, Fargo, ND.

Franzen, M. 2012. Program for initial analysis of GreenSeeker® and Holland Crop Circle® Sensor raw data within Excel. Unpublished program. Fargo, ND.

Gates, D. M., H.J. Keegan, J.C. Schleter, and V.R. Weidner. 1965. Spectral properties of plants. Appl. Optics. 4:11–20.

Gausman, H.W. 1982. Increased cotton plants heat tolerance by mepiquat chloride. Technical reports, Bull. Plant Growth Regul. 10:6-8.

Gausman, H.W. 1977. Reflectance of leaf components. Remote Sens. Environ. 6:1-9.

Gausman, H. W., and W. A. Allen. 1973. Optical parameters of leaves of 30 plant species. Plant Physiol. 52: 57–62.

Gausman, H.W., W.A. Allen, R. Cardenas, and A.J. Richardson. 1971. Effects of leaf nodal position on absorption and scattering coefficients and infinite reflectance of cotton leaves, Gossypium hirsutum L. Agron. J. 63:87–91.

Gitelson A.A., and M.N. Merzlyak. 1997. Remote estimation of chlorophyll content in higherplant leaves. J. Remote Sens. 18:2691-2697.

Harapiak, J.T. 1980. Rapeseed response to sulphur, boron, and fertilizer placement. Proc. Soils and Crops Workshop, February 1980, University of Saskatchewan, Saskatoon, SK. Pp 145–154.

Hatfield, J.L., A.A. Gitelson, J.S. Schepers, and C.L. Walthall. 2008. Application of spectral remote sensing for agronomic decisions. Agron. J. 100:117-131.

Horler, D.N.H., M. Dockray and J. Barber. 1983. The red-edge of plant leaf reflectance. Int. J. Remote Sens. 4:273—288.

Lindsay, W.L., and W.A. Norvell. 1978. Development of a DTPA soil test for zinc, iron, manganese, and copper. Soil Sci. Soc. Am. J. 42:421–428.

Ma, B.L., M.J. Morrison, and L.M. Dwyer.1996. Canopy light reflectance and field greenness to assess nitrogen fertilization and yield of corn. Agron. J. 88:915-920.

Malhi, S.S., and K.S. Gill. 2006. Cultivar and fertilizer S rate interaction effects on canola yield, seed quality and S uptake. Can. J. Plant Sci. 86:91–98.

Masoni, A., L. Ercoli, and M. Mariotti. 1996. Spectral properties of leaves deficient in iron, sulfur, magnesium, and manganese. Agron. J. 88:937-943.

Maas, S. J., and J.R. Dunlap. 1989. Reflectance, transmittance, and absorptance of light by normal, etiolated, and albino corn leaves. Agron. J. 81:105–110.

Milton, N.M., C.M. Ager, B.A. Eiswerth, and M.S. Power. 1989. Arsenic- and selenium-induced changes in spectral reflectance and morphology of soybean plants. Remote Sens. Environ. 30:263-269.

Milton, N.M., B.A. Eiswerth, and C.M. Ager. 1991. Effect of phosphorus deficiency on spectral reflectance and morphology of soybean plants. Remote Sens. Environ. 36:121- 127.

Mistele, B. and U. Schmidhalter. 2008. Estimating the nitrogen nutrition index using spectral canopy reflectance measurements. Eur. J. Agron. 29:184-190.

Nuttall, W.F., H. Ukrainetz, J.W.G. Stewart, and D.T. Spurr. 1987. The effect of nitrogen, sulphur and boron on yield and quality of rapeseed (Brassica napus L. and B. campestris L.). Can. J. Soil Sci. 67: 545–559.

Olsen, S.R., C.V. Cole, F.S. Watanabe, and L.A. Dean. 1954b. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circular 939. U.S. Government Printing Office, Washington, D.C.

Raun, W.R., J.B. Solie, J.B., G.V. Johnson, M.L. Stone, E.V. Lukina, and W.E. Thompson. 2001. Agron. J. 93:131-138.

Ridley, A. O. 1972. Effect of nitrogen and sulfur fertilizers on yield and quality of rapeseed. Proc. 16th Annual Manitoba Soil Science Meeting, January 1972, University of Manitoba, Winnipeg, MB. Pp. 149–155.

Ridley, A. O. 1973. Effect of nitrogen and sulfur fertilizers on yield and quality of rapeseed. Proc. 17th Annual Manitoba Soil Science Meeting, January 1972, University of Manitoba, Winnipeg, MB. Pp. 182–187.

Schulte, E.E., and B.G. Hopkins. 1996. Estimation of soil organic matter by weight-loss-on ignition. In F.R. Magdoff et al. (Eds.), Soil Organic Matter: Analysis and Interpretation (Chap. 3, pp. 21–31). SSSA Special Publication 46. Madison, WI: SSSA.

Schulte, E.E., and Kalju Elk. 1988. Recommended sulfate-S test. P. l7-20. In W.C. Dahnke (ed.). Recommended chemical soil test procedures for the North Central Region. North Dakota Agric. Exp. Stn. Bull. 499.

Solari, F., J. Shanahan, R.B. Ferguson, J.S. Schepers, and A.A. Gitelson. 2008. Active sensor reflectance measurements of corn nitrogen status and yield potential. Agron. J. 100:571-579.

Thomas, G.W. 1982. Exchangeable cations. In A. L. Page et al. (Eds.). Methods of soil analysis. Part 2. (Agronomy Monographs 9, pp. 159–165). Madison, WI: ASA and SSSA.

Walburg, G., M.E. Bauer, C.S.T. Daughtry, and T.L. Housley. 1982. Effects of nitrogen nutrition on the growth, yield, and reflectance characteristics of corn canopies. Agron. J. 74:677–683.

Wolfe, D.W, D.W. Henderson, T.C. Hsiao, and A. Alvino. 1988. Interactive water and nitrogen effects on senescence of maize. II. Photosynthetic decline and longevity of individual leaves. Agron. J. 80:865-870.

CHAPTER VIII. OVERALL CONCLUSION

The GS sensor using the red band and the CC using both red and red-edge NDVI options were found useful in predicting the yield under both medium texture and eastern high clay conventional-till sites. When the sensor reading INSEYmultiplied with corn height it often increased the yield prediction relationship. However, during the drought year of 2012, the sensors and height were least useful in the eastern no-till sites. Although height did not improve the relationship at V12, but the eastern no-till sites sensor relationships in 2011 were significant for all sensors. In general, the height addition to sensor readings was most helpful at V6 and V12 stage for the GS and CC using the red NDVI. although crop height improved the CC red-edge NDVI relationship with yield occasionally but the frequency of improvement was poor than with the CC and GS red NDVI option red NDVI and yiled relationships provide a two-dimensional reading measurement of crop canopy, whereas the CC red-edge sensor reads more like the human eye in detection of greenness of the crop. Although the height measurements in these experiments were conducted manually, commercial adoption of algorithms that include height will require automated means for accumulating partner height data along with simultaneous collection of sensor readings.

Comparing two sensors for their ability to predict the yield early in the season (at V6 or V12 growth stage of corn), CC performed better than GS due to the option of using red-edge NDVI, which outperformed than other two red NDVI options both from CC and GS. The relationship between INSEY and yield at V6 stage was significant for both the GS and CC Red NDVI and CC Red-edge NDVI in the eastern medium-textured 207onventional-till sites soil category under conventional tillage. The relationship between INSEY and yield under eastern medium-textured 207onventional-till sites was higher with the CC red-edge NDVI as compared to GS and CC red NDVI at V12.

In the eastern no-till sites site category, the INSEY to yield relationship for both sensors was significant at the V12 stage in 2011, but not in 2012, because the relationship between years was very different in 2011 compared to 2012, a combined analysis was not conducted. The lack of INSEY relationship to yield in 2011 and 2012 at the V6 stage might be explained by slow early corn growth in each year under eastern no-till sites compared to the conventional tillage sites. At V12 in 2011, the prediction of yield was improved, probably because the earlier detrimental effects of residue cover were diminished with time and soil warming. In 2012, however, abnormally dry soil conditions beginning in mid-July of 2011 resulted in over estimation of corn yield at both sensing periods compared to achieved yields at most sites.

Within the eastern high clay conventional-till sites conventional category and all categories combined, the relationship between INSEY and yield was significant at both the V6 stage and the V12 stage. The INSEY and yield relationship of both sensors was higher at V12 stage during 2011 as compared to 2012 and all sites together. The CC red-edge INSEY was generally better related to yield at V12 during 2011. The CC Red NDVI was similar to the GS Red NDVI in predicting yield.

While preparing the algorthims using sensor reading, all the models wer significantly better but red-edge INSEY model was comparatively better than other two INSEY mdoels. The algorithms produced through the present study could give more precise in-season N rate calculations than other conventional sensor based algorithms because specific soil or cultivation systems have been considered while building the N rate algorithm whereas other researchers gave more gerneralized N rate models. Two sensing times (V6 and V12) have been found to give significant estimation of yield. The V6 sensing was found weaker than V12 and no relationship was detected under low yielding eastern high clay conventional-till sites, eastern medium-textured conventional-till sites and eastern no-till sites, whereas V12 was found weak only under low yielding eastern medium-textured 209onventional-till sites. The weak relationship in the lower yielding eastern high clay conventional-till sites and eastern medium-textured 209onventional-till sites was probably the result of denitrification in the eastern high clay conventional-till sites and leaching in the eastern medium-textured 209onventional-till sites. These results indicate that in practice, the algorithms for the higher yielding eastern high clay conventional-till sites and eastern medium-textured 209onventional-till sites should be used, since application at V6 would often be made after the seasonal N loss period was over. The weak relationship between yield and sensor INSEY at long-term eastern no-till sites is might be due to slower growth in cooler soils, with the sensors underestimating yield potential therefore, delaying supplemental N application about V12 would not be expected to hold back yield, and algorithms developed by V12 would help capture higher yields through late in-season N application. Three wavelength combinations provided good relationships with yield. the value of regression coefficient confirmed that the red-edge wavelength (730nm) generally performed better than the other two red wavelengths, 656 and 670nm, from GS and CC, respectively at V12, and the red-edge was similar to the red wavelengths at V6.

Using active optical sensors to detect S defficencies with N rich strip produced significant results. Significant differences in readings within the N rate treatment was observed both at V6 due to S deficiency. The readings were decreasing with increasing in N rate due to S deficiency at V6 growth stage. The CC was genrally better than GS in detecting S deficiency because regression coeffeicent determined with CC wavelength was better than GS wavelength. The differences in abilities of sensors to detect S deficiency was due to different range of red and red-edge INSEY were used in both the sensors.

APPENDIX A. CHEMICAL DATA OF NITRATE-NITROGEN, POTASSIUM, PHOSPHORUS, ZINC, OGANIC MATTER, AND pH FROM CHAPTER III.

Year	Locations	Soil Depth	NO_3^-	P	K	Zn	OM	pH†
			ppm				%	
2011	Valley City	0-6	6	16	160	0.6	3.6	5.7
		0-24	15					
	Rutland	0-6	7	15	355	1.47	5.4	NA
		0-24	12					
	Havana	0-6	10	21	540	2.2	7.3	NA
		0-24	18					
	Milnor	0-6	10	12	115	0.95	2.7	NA
		0-24	18					
	Durbin	0-6	3	19	400	0.96	4.4	7.3
		0-24	4.5					
	Moorton	0-6	5.5	12	350	1.04	3.9	7.1
		0-24	15					
	Great bend	0-6	8.5	28	380	1.2	4.4	NA
		0-24	12					
	Fairmount 2	0-6	12	12	177	1.5	4.7	7.3
		0-24	12.5					
	Buffalo	0-6	4.5	9	130	0.41	3.5	7.2
		0-24	15					
	Walcott	0-6	4.5	6	128	1.45	4.5	8
		0-24	6					
	Arthur	0-6	7.5	9	169	1.19	2.7	6.6
		0-24	12					
	Christine	0-6	11	13	385	1.59	4.9	6.7
		0-24	19.5					
	Prosper	0-6	6.5	6	285	0.49	5	7.9
		0-24	15					
	Page 2	0-6	5.5	4	175	1.04	4.1	7.2
		0-24	13.5					
2012	Leonard	0-6	18	8	330	1.13	4.3	7.1
		0-24	34.5					
	Leonard South	0-6	8	4	90	1.94	2.2	7.6
		0-24	10.5					
	Walcott West	0-6	8	4	80	1.26	3.1	8.1
		0-24	24					
	Casselton South	0-6	10	15	370	1.05	5.4	7.8
		0-24	9					
	Arthur	0-6	20	81	540	4.67	4	6.9
		0-24	40					

(continues)

Year	Locations	Soil Depth	$NO_{3^-}^-$	P	K	Zn	OM	pH†
			ppm				%	
2012	Wheatland	0-6	16.5	25	120	0.33	2.6	7.1
		0-24	19.5					
	Milnor	0-6	12	13	300	1.22	4.1	7.4
	Wheatland	0-6	16.5	25	120	0.33	2.6	7.1
		0-24	21					
	Rutland East	0-6	9	6	280	0.75	4.4	7.7
		0-24	7.5					
	Rutland west	0-6	17.5	8	40	0.71	5.5	7.8
		0-24	18					
	Walcott East	0-6	12	12	100	3.11	2.3	7.3
		0-24	18					
	Casselton North	0-6	15.5	10	450	0.96	5.5	7.3
		0-24	18					
	Galchutt	0-6	12.5	25	405	2.68	4.6	7.9
		0-24	9					
	Fairmount West	0-6	24	11	160	1.63	4.1	7.9
		0-24	19.5					
	Fairmount South	0-6	20	16	180	0.72	4.1	7.8
		0-24	15					
	Great bend	0-6	19.5	26	430	1.28	5.4	6.3
		0-24	24					
	Gardner	0-6	14.5	10	20	,63	2.3	6.7
		0-24	25.5					
	Prosper	0-6	20	16	435	0.72	5.5	7.1
		0-24	12					
	Barney	0-6	22.5	48	560	2.03	4.2	7
		0-24	33					
2013	Casselton Seed	0-6	19	7	370	0.37	5.4	7.6
		0-24	49.5					
	Leonard-North	0-6	5.5	18	380	0.95	5.7	6.6
		0-24	13.5					
	Durbin	0-6	5	34	460	0.62	5.9	7.5
		0-24	40.5					
	Arthur	0-6	5	9	110	1.16	2.2	6.6
		0-24	10.5					
	Leonard West	0-6	6.5	8	125	3.75	2.2	7.3
		0-24	10.5					
	Barney	0-6	21.5	12	110	1.21	2.9	7.8
		0-24	81					
	Dwight	0-6	32	63	540	2.37	4	7.7
		0-24	234					

(contunues)

Year	**Locations**	**Soil Depth**	**NO^{-}_{3}-**	**P**	**K**	**Zn**	**OM**	**pH**†
			ppm				**%**	
	Rutland	0-6	18	8	415	0.72	6.1	7
		0-24	48					
	Oakes	0-6	4.5	11	210	1.93	3.3	5.4
		0-24	13.5					
	James town	0-6	8.5	8	220	1.14	3.3	5.7
		0-24	10.5					
	Dwight	0-6	10.5	8	185	0.45	3.5	7.9
		0-24	64.5					
	Mott	0-6	16	4	230	0.95	5.2	7.6
		0-24	9					
	Richardton	0-6	9.5	33	170	0.65	3.2	5.1
		0-24	7.5					
	Beach	0-6	15.5	22	300	0.85	3	6.2
		0-24	6					
	New Leipzig	0-6	21	16	560	1.46	5.2	5.6
		0-24	16.5					

†NA=data not available

APENDIX B. YIELD AND TREATMENT ANALYSIS WITH SAS AND THEIR LSD VALUES (SAS OUTPUT)

SAS treatment and yield data analysis for all the sites from 2011 and 2012

****

The SAS System 22:40 Wednesday, March 6, 2013 336

The GLM Procedure

Class Level Information

Class	Levels	Values
REP	4	1 2 3 4
TRT	6	1 2 3 4 5 6

Number of Observations Read 816

Number of Observations Used 816

****

The SAS System 22:40 Wednesday, March 6, 2013 337

The GLM Procedure

Dependent Variable: Y

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	443073408	55384176	5.00	<.0001
Error	807	8934058974	11070705		
Corrected Total	815	9377132382			

R-Square Coeff Var Root MSE Y Mean

0.047250	33.47581	3327.267	9939.316

Source	DF	Type I SS	Mean Square	F Value	Pr > F
REP	3	8779622.5	2926540.8	0.26	0.8511
TRT	5	434293785.6	86858757.1	7.85	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	3	9634928.9	3211643.0	0.29	0.8326
TRT	5	434293785.6	86858757.1	7.85	<.0001

****

The SAS System 22:40 Wednesday, March 6, 2013 338

The GLM Procedure

t Tests (LSD) for Y

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	807
Error Mean Square	11070705
Critical Value of t	1.96291
Least Significant Difference	792.01

Means with the same letter are not significantly different.

t Grouping	Mean	N	TRT
A	10646.3	136	5
A			
A	10576.6	136	4

A

A 10529.8 136 6

A

B A 9930.1 136 3

B

B C 9174.9 136 2

C

C 8778.2 136 1

****

SAS treatment and yield data analysis from high clay sites from 2011 and 2012

The SAS System 20:40 Monday, May 27, 2013 1

The GLM Procedure

Class Level Information

Class	Levels	Values
REP	4	1 2 3 4
TRT	6	1 2 3 4 5 6

Number of Observations Read 336

Number of Observations Used 336

****

The SAS System 20:40 Monday, May 27, 2013 2

The GLM Procedure

Dependent Variable: Y

Sum of

Source	DF	Squares	Mean Square	F Value	Pr > F
Model	8	195794848	24474356	1.91	0.0575
Error	327	4185447432	12799533		
Corrected Total	335	4381242280			

R-Square	Coeff Var	Root MSE	Y Mean
0.044689	38.62073	3577.644	9263.531

Source	DF	Type I SS	Mean Square	F Value	Pr > F
REP	3	9604311.6	3201437.2	0.25	0.8612
TRT	5	186190536.4	37238107.3	2.91	0.0138

Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	3	9604311.6	3201437.2	0.25	0.8612
TRT	5	186190536.4	37238107.3	2.91	0.0138

****

The SAS System 20:40 Monday, May 27, 2013 3

The GLM Procedure

t Tests (LSD) for Y

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	327
Error Mean Square	12799533
Critical Value of t	1.96725
Least Significant Difference	1330.1

Means with the same letter are not significantly different.

t Grouping	Mean	N	TRT
A	10064.7	56	5
A			
A	9953.1	56	6
A			
B A	9675.0	56	4
B A			
B A C	9314.7	56	3
B C			
B C	8539.6	56	2
C			
C	8034.2	56	1

****

SAS treatment and yield data SAS analysis for medium textured sites

The SAS System 19:17 Monday, May 27, 2013 16

The GLM Procedure

Class Level Information

Class	Levels	Values
REP	4	1 2 3 4
TRT	6	1 2 3 4 5 6

Number of Observations Read 288

Number of Observations Used 288

****

The SAS System 19:17 Monday, May 27, 2013 17

The GLM Procedure

Dependent Variable: Y

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	123671619	15458952	2.32	0.0198
Error	279	1855922344	6652051		
Corrected Total	287	1979593963			

R-Square	Coeff Var	Root MSE	Y Mean
0.062473	24.66756	2579.157	10455.66

Source	DF	Type I SS	Mean Square	F Value	Pr > F
REP	3	326476.4	108825.5	0.02	0.9971
TRT	5	123345142.9	24669028.6	3.71	0.0029

Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	3	326476.4	108825.5	0.02	0.9971
TRT	5	123345142.9	24669028.6	3.71	0.0029

****

The SAS System 19:17 Monday, May 27, 2013 18

The GLM Procedure

t Tests (LSD) for Y

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error

Alpha 0.05

Error Degrees of Freedom 279

Error Mean Square 6652051

Critical Value of t 1.96850

Least Significant Difference 1036.4

Means with the same letter are not significantly different.

t Grouping		Mean	N	TRT
	A	11206.6	48	6
	A			
	A	10947.6	48	5
	A			
	A	10902.7	48	4
	A			
B	A	10514.4	48	3
B				
B	C	9707.4	48	2
	C			
	C	9455.3	48	1

****

SAS treatment and yield data analysis for no-till sites from 2011 and 2012

The SAS System 19:17 Monday, May 27, 2013 10

The GLM Procedure

Class Level Information

Class	Levels	Values
REP	4	1 2 3 4
TRT	6	1 2 3 4 5 6

Number of Observations Read 120

Number of Observations Used 120

****

The SAS System 19:17 Monday, May 27, 2013 11

The GLM Procedure

Dependent Variable: Y

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	134481285.8	16810160.7	7.76	<.0001
Error	111	240435049.6	2166081.5		
Corrected Total	119	374916335.4			

R-Square	Coeff Var	Root MSE	Y Mean
0.358697	16.66589	1471.761	8830.978

Source	DF	Type I SS	Mean Square	F Value	Pr > F
REP	3	8456156.7	2818718.9	1.30	0.2777
TRT	5	126025129.1	25205025.8	11.64	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	3	11368878.3	3789626.1	1.75	0.1611
TRT	5	126025129.1	25205025.8	11.64	<.0001

****

The SAS System 19:17 Monday, May 27, 2013 12

The GLM Procedure

t Tests (LSD) for Y

NOTE: This test controls the Type I comparisonwise error rate, not the experimentwise error rate.

Alpha	0.05
Error Degrees of Freedom	111
Error Mean Square	2166082
Critical Value of t	1.98157
Least Significant Difference	922.24

Means with the same letter are not significantly different.

t Grouping		Mean	N	TRT
	A	9994.5	20	5
	A			
B	A	9624.3	20	6
B	A			
B	A	9446.4	20	4
B				
B		8963.6	20	3
	C	7721.3	20	2
	C			
	C	7235.7	20	1

APENDIX C. SAS CODES USED FOR THE ANALYSIS OF THE THIS STUDY

Compare regression lines (regression coefficient)

```
proc print;

title2 'Check Data';

run;

ods rtf file='compare_lines.rtf';

ods graphics on;

proc glm;

class Soil;

model YldKg = CCV1 Soil CCV1*Soil / solution;

title2 'Compare Regression Lines for CCV1';

run;
```

Compare yield and N treatment LSD

```
proc glm;

class rep trt;

model Y=rep trt;

means trt/lsd;

run;
```

Compare different models

```
options formdlim='*';

data Arthur2011;

input CCV1 Y;

CCV12=CCV1*CCV1;

CCV12=CCV1**2;
```

```
SQRTCCV1=SQRT(CCV1);

LNCCV1=log(CCV1);

LNY=Log(Y);

Proc Reg;

Model Y=CCV1;

Run;

Proc Reg;

Model Y=CCV1 CCV12;

Run;

Proc Reg;

Model Y=SQRTCCV1;

Run;

Proc Reg;

Model Y=LNCCV1;

Run;

Proc Reg;

Model LNY=LNCCV1;

Run;
```