

DEVELOPING A CROP BASED STRATEGY FOR ON-THE-GO NITROGEN
MANAGEMENT IN IRRIGATED CORNFIELDS

By

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DEVELOPING A CROP BASED STRATEGY FOR ON-THE-GO N MANAGEMENT
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Traditional nitrogen (N) management schemes for corn production systems in the Corn Belt have resulted in low N use efficiency (NUE), environmental contamination, and considerable debate regarding use of N fertilizers in crop production. The major causes for low NUE of traditional N management practices are: 1) poor synchrony between soil N supply and crop demand, 2) field uniform applications to spatially-variable landscapes that commonly have spatially-variable crop N need, and 3) failure to account for temporal variability and the influence of weather on mid-season N needs. Therefore, the objective of this work was to develop a reflectance-based technology for in- season and on-the-go nitrogen (N) fertilizer management in irrigated cornfields. First, a series of experiments were conducted to answer relevant questions pertaining to sensor positioning and orientation to maximize sensitivity for biomass and N status estimation. The second objective was to assess chlorophyll (Chl) status in cornfields using active crop canopy sensor readings by means of comparing the results with relative chlorophyll meter data (SPAD) units. Sensor and SPAD readings were collected in three cornfields in central Nebraska from V9 to R4. Finally an algorithm for in-season N management based on active sensor readings was developed using ancillary data from a long-term study. The

results indicate that sensor readings provide information not only about relative Chl content but also about plant distribution and biomass. The four vegetation indices evaluated were linearly related with relative SPAD readings during vegetative growth stages. RWDRVI, RChl index, and RAR showed more sensitivity than RANDVI to variations in relative Chl content. It also was found that 1) sensors can be used to predict N availability to the crop, 2) N deficiencies can be corrected depending on the degree of stress, 3) A $SI_{\text{SENSOR}} < 0.78$ during the period V11-V15 may indicate irrecoverable yield loss. Active sensor technology can be used for on-the-go assessment of N status in irrigated cornfields. At this point the model developed is site-specific and needs to be tested in other environments.

Key words: nitrogen, corn, reflectance, active sensors, vegetation indices

...reality has not the slightest obligation to be interesting. I will reply in turn that reality may get along without that obligation, but hypotheses may not.

Death and the compass

JLB

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General Introduction

Fernando Solari

Current N management schemes for world cereal production systems have resulted in low NUE, with estimates averaging only around 33% of fertilized N recovered (Raun and Johnson, 1999). At \$850 per metric ton of N fertilizer, the unaccounted 67% represents a \$28 billion annual loss of fertilizer N (assuming fertilizer–soil equilibrium). Pathways for N losses from agroecosystems include gaseous plant emissions, soil denitrification, surface runoff, volatilization, and leaching (Raun and Johnson, 1999). With the exception of N denitrified to N₂, these pathways lead to an increased load of biologically reactive N into external environments (Cassman et al., 2002). In the U.S. for example, the amount of biologically reactive N delivered from the land to coastal waters has increased dramatically over the past century (Turner and Rabalais, 1991), and has been a primary causal factor in oxygen depletion of coastal waters (Rabalais, 2002). Current fertilizer N management practices in the Corn Belt, especially practices where N fertilizer is applied at rates beyond crop needs (Burwell et al., 1976), have led to nitrate-N being the most common contaminant found in the surface and ground waters of the region (Schilling, 2002; Steinheimer et al., 1998; CAST, 1999). In summary, traditional N management schemes for cereal production systems in the U.S. and around the world have resulted in low N use efficiency (NUE), environmental contamination, and considerable public debate regarding use of N fertilizers in crop production. Hence, development of alternative N management strategies that maintain crop productivity,

improve NUE, and minimize environmental impact will be crucial to sustaining cereal production systems worldwide.

Causes of Low NUE for Current N Management Schemes

One of the major causes for low NUE of current N management practices is poor synchrony between soil N supply and crop demand (Raun and Johnson, 1999; Cassman et al., 2002; Fageria and Baligar, 2005). Poor synchronization is mainly due to large pre-plant applications of fertilizer N. Cassman et al. (2002), for example, estimated from USDA statistics (USDA-NASS, 2003) that typical N application amounts in the U.S. Corn Belt region averaged (last 20 yrs) approximately 150 kg ha^{-1} , with farmer surveys indicating around 75% of the applications occurring prior to planting (including the previous fall) and only 25% of the applications made after planting. In the first three weeks after emergence, corn takes up soil mineral N (SMN) at a rate less than $0.5 \text{ kg ha}^{-1} \text{ day}^{-1}$ (Schröder et al., 2000). During that period, depending on weather and soil conditions, excess N may move from the rooting zone and ultimately be lost. During the next 75 days approximately constant maximal rates can be as high as $3.7 \text{ kg ha}^{-1} \text{ day}^{-1}$ (Andrade et al., 1996) with peaks of $6 \text{ kg ha}^{-1} \text{ day}^{-1}$ (J.S. Schepers, personal communication). At silking total N accumulated by corn plants is around 60% of total N absorbed at harvest (Aldrich and Leng, 1974; Andrade et al., 1996). Hence, these large pre-plant N applications result in high levels of available soil profile N, well before active crop uptake occurs, resulting in poor synchrony between soil N supply and crop demand. Efficiency of use from a single pre-plant N-fertilizer application typically decreases in proportion to the amount of N fertilizer applied (Reddy and Reddy, 1993). Other studies have substantiated that in-season applied N results in a higher NUE than when N is pre-

plant applied (Miller et al., 1975; Olson et al., 1986; Welch et al., 1971). Collectively, these results agree with the recommendations of Keeney (1982), who over twenty years ago advocated that the most logical approach to increasing NUE is to supply N as it is needed by the crop. This reduces the opportunity for N loss because the plant is established and in the rapid uptake phase of growth. Thus, while research is rich with results supporting the point that NUE is improved by synchronizing applications with crop N use, adoption by farmers with this as the reason for changing has been minor. The barrier has primarily been a lack of cost-effective and/or practical technologies to implement in-season N applications (Cassman et al., 2002).

Another major factor contributing to low NUE in current schemes has been uniform application rates of fertilizer N to spatially-variable landscapes, even though numerous field studies have indicated economic and environmental justification for spatially variable N applications in many agricultural landscapes (Mamo et al., 2003; Hurley et al., 2004; Koch et al., 2004; Scharf et al., 2005; Shahandeh et al., 2005; Lambert et al., 2006). Uniform applications within fields discount the fact that N supplies from the soil, crop N uptake, and responses to N are not the same spatially (Inman et al., 2005). Thus, when N is applied as large preplant doses at field uniform rates it is at considerable risk for environmental loss.

A third reason for low NUE is attributed to the way N fertilizer requirements are commonly derived. Many current fertilizer N recommendation procedures are yield-based, meaning they rely on expected yield (also called target yield or yield goal) multiplied by some constant factor, representing the N concentration of grain, to come up with the N fertilizer requirement. This calculation produces a number that is, in essence,

an estimate of the amount of N that will be removed from the field due to harvest of the crop (Stanford and Legg, 1984; Meisinger and Randall, 1991). Adjustments to the calculated fertilizer recommendation are made for various N credits, such as previous crop and recent use of manure (Mulvaney et al., 2005). While this “mass balance” approach is simple and holds considerable appeal, it is not without its shortcomings. One major weakness inherent in this approach is that it assumes a constant NUE (Meisinger, 1984; Meisinger et al., 1992), when research has shown that NUE varies dramatically from site to site and year to year. From plot research, it rarely exceeds 70% (Pierce and Rice, 1988) and more often ranges from 30-60% (Bock, 1984). The other difficulty is in deriving an accurate and realistic estimate of the target yield, particularly for rain-fed cropland with precipitation varying seasonally as well as annually. A number of approaches for determining target yield have been considered. Averaging yields over a number of years can be used, but this method may result in inadequate N for years when conditions provide better than average yield. A target yield that is based upon only the best recent years will generally meet crop N needs, but potentially will leave inorganic N in the soil when growing conditions have not been ideal. Target yield is often determined by adding 5 to 10 % to the average yield of the most recent 5 to 7 years (Rice and Havlin, 1994).

Surveys have demonstrated that a majority of producers over-estimate their target yield when determining N recommendations (Schepers and Mosier, 1991; Goos and Prunty, 1990), because of the historic low cost to apply ample N fertilizer to insure it will not be limiting, regardless of the type of year. Inflated target yield may also suggest producers do not use actual whole-field averages, but rather rely upon yield expectations

from the highest producing field areas. Even before the availability of combines with yield monitoring systems, farmers intuitively have known that for a field-average yield of 10 Mg ha⁻¹ corn, there were areas within that same field that probably produced 12 to 14 Mg ha⁻¹.

The deficiencies of the yield-based approach in making N recommendation is substantiated in a study conducted by Lory and Scharf (2003), where data from 298 previously reported experiments in five Corn Belt states in the U.S. were combined to evaluate corn yield response to fertilizer N. In this study, recommended N rates as determined by actual yield exceeded the economically optimum N rate (EONR) by up to 227 kg ha⁻¹ and on average by 90 kg ha⁻¹. Furthermore, recommended N rates were not highly correlated ($r = 0.04$) with EONR. Thus, using an expected yield would have provided no predictive value for making N recommendations on these study areas, and it actually over-recommended N application in many instances. Researchers in Iowa (Blackmer et al., 1997), Wisconsin (Vanotti and Bundy, 1994; Bundy, 2000), Pennsylvania (Fox and Piekielek, 1995), and Ontario (Kachanoski et al., 1996) also identified problems in using expected yield in making N recommendations, raising concerns about the reliability of using yield in the N rate recommendation.

In spite of these findings showing yield may be poorly correlated with crop N need, yield as a basis for N application has wide-spread appeal with many farmers and researchers. Generally, crop-N demand is determined by biomass yield and the physiological requirements for tissue N, with C₄ crops like corn requiring less N to produce a given level of biomass than C₃ crops like wheat (Gastal and Lemaire, 2002). Crop-management practices and climate have the most influence on yield. Climate can

vary significantly from year to year, which causes large differences in yield potential. In irrigated systems, the yield potential of a specific crop cultivar is largely determined by solar radiation and temperature. In rainfed systems, rainfall amount and temporal distribution have the greatest influence on yield potential. While solar radiation, temperature, and moisture regimes determine the genetic yield ceiling, actual crop yields achieved by farmers are generally far below this threshold because it is neither possible, nor economical, to remove all limitations to growth from sub-optimal nutrient supply, weed competition, and damage from insects and diseases. Hence, the interaction of climate and management causes tremendous year-to-year variation in on-farm yields and crop N requirements.

In summary, it is not surprising that current N management schemes have resulted in such low NUE values, given that current practices typically utilize a suspect approach in estimating crop fertilizer N requirements, make use of large pre-plant N applications (i.e., lack of synchrony), and ignore within-field variability in N fertilizer need. The key to optimizing the tradeoff amongst yield, profit, and environmental protection for future N management practices is to achieve synchrony between soil N supply and crop demand, and account for landscape spatial variability in soil N supplies and crop N uptake. This means less dependence on large pre-plant applications of uniformly applied N and greater reliance on a “reactive approach” that involves in-season estimates of crop N needs with the ability to adjust for both temporal and spatial variability effects on soil and crop N dynamics. To accomplish this task it will be necessary to utilize various precision agriculture tools like on-the-go soil and crop sensors that have the ability to

remotely sense soil N supply and crop N status in “real-time”, and deliver spatially-variable N applications based on crop N need.

New Nitrogen Management Strategies Using Precision Agriculture Technologies

Precision agriculture includes a wide range of geospatial technologies that have become available to agriculture since the mid 1990s. These technologies have been made possible by low cost global positioning systems (GPS) and mobile data processing equipment capable of storing and retrieving large databases. Some of these developments have provided detailed geographical information system (GIS) spatial databases for traditional elements of the N recommendation algorithms such as soil survey maps, yield maps, previous crops, and soil test results. Satellite and aircraft can also provide remotely sensed data on soil moisture content, residue cover, and crop stress. On-the-ground soil sensors have also been developed for assessing soil electrical conductivity, sub-soil compaction, and soil organic matter. Real-time crop sensors have also become available utilizing passive and active technologies to ascertain crop stress (such as apparent N status) through reflectance measurements in the visible and near-infrared wavelengths.

Management Zone Approach

To accommodate spatially variable landscape conditions and better match N supply with crop N requirements, some (Franzen et al., 2002; Ferguson et al., 2003) have advocated a soil-based approach involving delineation of spatial variability into management zones (MZ) as a means to direct variable N applications and improve NUE. Management zones, in the context of precision agriculture, are field areas possessing homogenous attributes in landscape and soil condition. When homogenous in a specific

area, these attributes should lead to similar results in crop yield potential, input-use efficiency, and environmental impact. Approaches to delineate MZ vary somewhat, but typical procedures involve acquiring various georeferenced data layers (i.e. topography, soil color, electrical conductivity, yield), traditional and geospatial statistical analyses on these layers, and delineation of spatial variation from these layers into MZ, as outlined by Schepers et al. (2004). Soil map units (Wibawa et al., 1993), topography (Kravchenko et al., 2000), remote sensing (Schepers et al., 2004), electrical conductivity sensors (Kitchen et al., 2003; Heiniger et al., 2003; Johnson et al., 2003), crop yield (Flowers et al., 2005; Kitchen et al., 2005) and producer experience (Fleming et al., 2004) have all been used with varying success to delineate MZ. Most of these sources for MZ delineation are static from year to year. While these static data sources for MZ delineation can be used to consistently characterize spatial variation in soil physical and chemical properties that partially affect crop yield potential, they are less consistent in characterizing spatial variation in actual crop yield and hence crop N requirements, because of the apparent effect of temporal variation on expression of 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, the static soil-based MZ concept alone will not be adequate for variable application of crop inputs like N, primarily because it does not address climate-mediated crop N demand.

Soil versus plant based approaches

Many efforts have been made in this direction. In the majority, approaches were based on soil processes (Schröder et al., 2000). In fact, and even though they vary widely among states, current fertilizer recommendations in the Corn Belt are based on soil

indicators. Some include yield goal (Nebraska, Kansas, Colorado, and Minnesota), soil organic matter content (Nebraska, Kansas, Colorado, Minnesota), residual soil nitrate-nitrogen content (Nebraska, Kansas, Colorado, Minnesota) and credits for nitrogen from legumes, manure, and irrigation water (see table 4 in Dobermann and Cassman, 2002).

An alternative or maybe a complimentary approach is to use plants and crops as indicators of the environmental status. Plants and crops are good indicators of environmental status since they integrate the cumulative effect of weather and management practices over the season. Typically, plants with increased levels of N availability have greater leaf N concentrations, more chlorophyll (Inada, 1965; Al-Abbas et al, 1974; Wolfe et al, 1988) and greater rates of photosynthesis (Sinclair and Horie, 1989). Leaf chlorophyll content estimated by chlorophyll meter readings correlated with corn yield just as well as leaf N concentration (Schepers et al., 1992a).

Total N concentration

The total N concentration of specific plant organs or the entire plant can be used to understand the relative N status of a crop, as for example, in the concept of N_{crit} . At any growth stage of a crop N_{crit} is defined as the minimum N concentration required for maximum crop growth rate (Ulrich, 1952). The N_{crit} can be assumed as a function of aboveground biomass, called the critical N dilution curve (Greenwood et al, 1990). Based on the N_{crit} , an N nutrition index (NNI) can be defined as the ratio of actual N concentration to N_{crit} (Lemaire et al., 1997, Gastal and Lemaire, 2002). An NNI value of 1.0 or larger indicates non-N-limiting growth, whereas NNI values below 1.0 correspond to N deficiency situations. The concept of N_{crit} was successfully applied to various crops, e.g., grasses (Lemaire and Salette, 1984), wheat (*Triticum aestivum* L.; Justes et al.,

1994), rapeseed (*Brassica napus* L.; Colnenne et al., 1998), rice (*Oryza sativa* L.; Sheehy et al., 1998), and grain sorghum (*Sorghum bicolor* L.; van Oosterom et al., 2001).

With respect to corn, the total N concentration of the whole crop at early growth stages (when corn is between 15 and 30 cm tall) does not provide a reliable tool for assessing N availability (Binford et al., 1992a). Isolated plants only have limited competition for light; and therefore N_{crit} will only slightly decline with increasing biomass, as explained by Plénet and Lemaire (1999). They assumed N_{crit} of the whole crop to remain constant in early growth stages, until around biomass $< 1 \text{ Mg DM ha}^{-1}$. Above the 1-Mg threshold, however, they verified the existence and the monomiality of the N_{crit} -to-biomass relationship up to silking plus 25 days. In a recent publication, Herrmann and Taube (2004) reported that the range of the critical nitrogen dilution curve for corn can be extended until silage maturity.

The concept of N_{crit} provides a sound agronomic and ecophysiological perspective for N management in crops. However, its practical use in commercial agriculture, especially in large areas, is unlikely to occur because it would demand extensive plant sampling, and would be time consuming during periods where decisions and corrections have to be made almost on-the-go. Nonetheless, it provides a framework for the development of an in-season “reactive approach” for applying N. The main technical challenge is to accurately and remotely sense the overall N uptake and biomass of a crop.

Crop reflectance

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 (Schröder et al., 2000).

Green plant leaves typically exhibit very low reflectance and transmittance in visible regions of the spectrum (i.e. 400 – 700 nm) due to strong absorptance by photosynthetic and accessory plant pigments (Chappelle et al., 1992). However, the pigments involved in photosynthesis (chlorophyll) absorb visible 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, therefore, give a good indication of leaf greenness. By contrast, reflectance and transmittance are both usually high in the near-infrared (NIR) region of the spectrum (~700-1400 nm) because there is very little absorptance by subcellular particles 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, and reflectance measurements at these wavelengths provide information on the amount of leaf relative to the amount of uncovered soil. The color of a crop is not just determined by the color of the leaves, but also by the color of the soil, particularly when the crop canopy is still open. Therefore, combinations of reflectance in different wavelengths are used to estimate biophysical characteristics of vegetation. A vegetation index is derived from reflectance (ρ) with respect to wavelength (λ), which is a function of chlorophyll content in leaves, leaf area index, and background scattering. Several vegetation indexes for estimation of biophysical characteristics of vegetation stands have been proposed. Normalized Difference Vegetation Index (NDVI, eq 1) (Deering et al, 1975)

$$\text{NDVI} = (\rho_{\text{NIR}} - \rho_{\text{red}}) / (\rho_{\text{NIR}} + \rho_{\text{red}}) \quad [1]$$

Where ρ_{NIR} is the reflectance in the near infrared region of the spectrum, and ρ_{red} is the reflectance in the red region of the spectrum.

and GreenNDVI (Gitelson et al., 1996, eq. 2)

$$\text{GNDVI} = (\rho_{\text{NIR}} - \rho_{\text{green}}) / (\rho_{\text{NIR}} + \rho_{\text{green}}) \quad [2]$$

Where ρ_{NIR} is the reflectance in the near infrared region of the spectrum, and ρ_{green} is the reflectance in the green region of the spectrum.

are good estimators of the fraction of photosynthetically active radiation absorbed (FAPAR). However, NDVI has the limitation that it saturates asymptotically under conditions of moderate-to-high aboveground biomass (LAI greater than 2) (Gitelson et al., 1996; Miyneni et al, 1997). While reflectance in the red region (ρ_{red}) exhibits a nearly flat response once the leaf area index (LAI) exceeds 2, the near infrared (NIR) reflectance (ρ_{NIR}) continue to respond significantly to changes in moderate-to-high vegetation density (LAI from 2 to 6) in crops. However, this higher sensitivity of the ρ_{NIR} has little effect on NDVI values once the ρ_{NIR} exceeds 30%. Gitelson (2004) proposed a modification of the NDVI, the Wide Dynamic Range Vegetation Index, $\text{WDRVI} = (a * \rho_{\text{NIR}} - \rho_{\text{red}}) / (a * \rho_{\text{NIR}} + \rho_{\text{red}})$, where the weighting coefficient a has a value of 0.1–0.2, increases correlation with vegetation fraction by linearizing the relationship for typical wheat, soybean, and maize canopies. The sensitivity of the WDRVI to moderate-to-high LAI (between 2 and 6) was at least three times greater than that of the NDVI. By enhancing the dynamic range while using the same bands as the

NDVI, the WDRVI enables a more robust characterization of crop physiological and phenological characteristics. In a recent study Viña et al (2004), demonstrate how WDRVI increases sensitivity in moderate to high vegetation stands when compared with NDVI.

VARI= $(\rho_{\text{green}} - \rho_{\text{red}}) / (\rho_{\text{green}} + \rho_{\text{red}})$, (Gitelson et al, 2002b) is a good estimator of vegetation fraction or percent of cover, however because NIR is not used in the index, is not recommended for LAI estimations.

Newly developed indices for remote sensing of biophysical characteristics allow us to accurately estimate pigments contents at leaf (Gitelson et al., 2001; Gitelson, et al, 2002b; Gitelson et al, 2003a) and canopy level (Gitelson et al. 2005.), LAI and green leaf biomass (Gitelson, et al., 2003a) and CO₂ flux exchange (Gitelson et al., 2003b). In general these indices follow a similar conceptual model:

$$[R(\lambda_1)^{-1} - R(\lambda_2)^{-1}] R(\lambda_3) \propto a_{\text{pigment}}$$

Where $R(\lambda_1)^{-1}$ is the inverse reflectance at a wavelength λ_1 which is intended to be maximally sensitive to the pigment in question; $R(\lambda_2)^{-1}$ is the inverse reflectance at a wavelength that is minimally sensitive to the pigment of interest, and for which the absorption by other constituents is almost equal to that at λ_1 ; and $R(\lambda_3)$ is the reflectance at a wavelength that is insensitive to the pigment and were backscattering controls reflectance.

In the particular case of the chlorophyll index (Gitelson et al., 2005), the model can be re-written as:

$$\text{Chl index} = [R(\text{green})^{-1} - R(\text{NIR})^{-1}] R(\text{NIR}) = [R(\text{NIR}) / R(\text{green})] - 1$$

Or

$$\text{Chl index} = \left[\frac{R(\text{red edge}) - R(\text{NIR})}{R(\text{NIR})} \right] \left[\frac{R(\text{NIR})}{R(\text{red edge})} \right]^{-1}$$

Use of remote sensing in production agriculture

Remote sensing has been largely used in natural resources for land cover and biomass estimation, and changes in land uses (Deering et al, 1975; Sala et al., 2000; Kogan et al., 2004; Henebry et al., 2005). During the last ten years, several efforts have been made to adopt this approach to commercial agriculture. Several studies have shown good relationships between spectral reflectance, chlorophyll content and N status in green vegetation (Bausch and Duke, 1996; Stone et al., 1996; Blackmer et al., 1996a; Osborne et al., 2002). Furthermore, relative techniques were developed for using a SPAD chlorophyll meter, color photography, or canopy reflectance factors to assess spatial variation in N concentrations across growers' cornfields (Schepers et al., 1992b; Blackmer et al., 1993; Blackmer et al., 1994; Blackmer et al., 1996a; Blackmer et al., 1996b; Blackmer and Schepers, 1996; Schepers et al., 1996). Aerial photography is a relatively inexpensive solution, yet image processing is time consuming, and also depends on clouds and climate. The concept of "spoon-feeding" N to the crop on an "as needed" basis (Schepers et al., 1995) is intended to reduce the potential for environmental contamination by N in corn production. This strategy is based on results obtained using the SPAD chlorophyll meter to monitor crop N status and applying fertilizer N as needed, via fertigation (injecting fertilizer into irrigation water). Using this "spoon feeding" technique from V8 (Ritchie et al., 1986) to R1, Varvel et al. (1997) were able to maintain crop yield with less N fertilizer compared to a uniform rate of 200 kg ha⁻¹. This strategy has the advantage that is highly efficient in N use, but is almost impractical when growers have to fertilize a great number of corn hectares in a short period of time. Bausch and

Duke (1996) developed an N reflectance index (NRI) from green and NIR reflectance of an irrigated corn crop. The NRI was highly correlated with an N sufficiency index calculated from SPAD chlorophyll meter data and provided a rapid assessment of corn plant N status for mapping purposes. A more recent study using the NRI to monitor in-season plant N resulted in reducing applied N using fertigation by 39 kg ha⁻¹ without reducing grain yield (Bausch and Diker, 2001). Because this index was based on the plant canopy as opposed to the individual leaf measurements obtained with the SPAD readings, it has potential for larger scale applications and direct input into variable rate fertilizer application technology. In the same way, Shanahan et al (2003) found that GreenNDVI was well correlated with SPAD readings for corn at V11 and could be used for on-the-go N corrections. Work by Osborne et al. (2002) shows that specific wavelengths for estimating crop biomass, nitrogen concentration, grain yield and chlorophyll meters reading change with growth stage and sampling date when working with N and water stress.

Despite these efforts, the use of remote sensing in commercial agricultural is still in its infancy, and especially, when it comes to translating reflectance data or a vegetation index into a fertilizer N recommendation.

Raun et al (2001, 2002) proposed the use of optical sensors for in-season N management in winter wheat fields. Their approach assumes that NDVI divided by the GDD accumulated at sensing (also called in-season yield estimator (INSEY)) is an estimator of growth rate of the crop, and that growth rate is linearly related with yield. The strengths of this approach for winter wheat resides in mainly two points: 1) NDVI is a good estimator of biomass (Deering et al, 1975; Stone et al, 1996; among others),

especially under conditions of biomass lower than 2 Mg of dry matter ha⁻¹, and 2) plant and tiller mortality is a common fact in Oklahoma's winter wheat fields due to cold and dry winters, and this enhance the relationship between NDVI and soil coverage. However, if we look at the relationship between INSEY and yield potential (Raun et al., 2001 figure 3 and Lukina et al, 2001 figures 3 and 4) the model fits different clouds where each cloud is a different experiment. The relation does not hold for each experiment and in some cases there is no relationship.

Irrigated corn presents several differences with respect to wheat. First, in general there is no problem of plant mortality (no existence of patches of bare soil). Second, the beginning of exponential growth and increase in N uptake is around V6-V8 with LAI values close to 2 and / or biomass around 4 Mg ha⁻¹ where NDVI saturates (Gitelson, 1996; Miyneni et al, 1997). Third, in wheat crops grain yield is positively related with the number of fertile tillers per unit of area (Harper, 1983; Sharma, 1995). On the other hand, corn yield on a field basis is not necessarily related with plant size or N uptake at V6-V8 (Binford et al., 1992b; Plénet, 1995; Plénet and Lemaire, 1999), neither is it related to crop growth rate in this phenological window. None of the yield components (except plants per ha) in a corn crop are being determined at this point. Even if a hierarchy among individual plants can be established at V6 (Madonni and Otegui, 2003), the number of grains per plant is related with growth rate at silking +/- 10 days (Hall et al., 1981; Andrade et al., 1999), and saturates at growth rates around 6g pl⁻¹ day⁻¹ or, in a crop basis, at 30 to 35 g m⁻² day⁻¹ (Andrade et al, 1996; Echarte et al, 2000). This implies that yield prediction in absolute terms (either in a plant or area basis) based on reflectance readings or some kind of plant-based indicator in the V6-V15 window is at least a

difficult task to perform. A prediction of relative yield, however, expressed as a percentage yield of a non-limiting plant or crop area is not impossible. Work by Vega and Sadras (2003) shows that plant growth rate in corn is linearly related to shoot biomass at the beginning of the critical period. In addition Echarte and Andrade (2003) reported that the harvest index was stable for corn released between 1965 and 1993. That means that in relative terms we might be able to predict yield potential, and or N response. This relative approach was used by Shanahan et al., (2001) and Scharf and Lory (2002) to predict corn yield using remote sensing imagery.

What we need?

A crop-based N management strategy should identify crops N needs and provide N in the amount required for optimal or most profitable yields while reducing environmental impacts. There is a need to develop stress detection algorithms that perform reliably across space and time. Techniques should be independent of location, soils, and management factors.

The objective of this research program was to develop a farmer friendly technology for on-the-go N management in irrigated cornfields. Particular objectives were: 1) to calibrate commercially available crop canopy sensors for N/Chl estimation in irrigated cornfields, 2) to develop a framework for in-season N fertilization based on sensor readings.

This dissertation is organized in three chapters. The first chapter summarizes results from several experiments, with the objectives of calibrating two active sensors, and understanding how different operational issues may affect sensors' outputs. Chapter

two shows how these active sensors can be used as “mobile SPADs” to estimate the relative N status in irrigated cornfields. The third chapter integrates results from 10 years of experiments at the MSEA site in Nebraska and experiments conducted during my program to propose a conceptual framework for on- the- go N management in cornfields using active canopy sensors.

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Chapter 1

Understanding how active sensors work

ABSTRACT

Understanding how active sensors work and how their output is influenced by issues like distance to canopy, orientation and position over the row, and canopy depth is crucial in developing a crop reflectance-based strategy for N management. The present chapter summarizes results from a series of experiments conducted to answer relevant questions related to active sensor operational issues. The effect of sensor positioning and orientation over the canopy and their effects on assessment of biomass and N status were tested using two different active canopy sensors, Crop Circle and GreenSeeker. Fundamental information was retrieved from these experiments: first, sensitivity prompted us to work between 60 and 110 cm over the canopy with the Crop Circle sensor and between 80 and 110 cm for the GreenSeeker sensor. Reflectance data from the individual bands are affected by the inverse square of the distance law. Therefore, variability in data from the NIR band for example, can be due to either distance between the sensor and top of the canopy or the amount of living vegetation in the field of view. Normalizing data from several bands removes the effect of distance because both are affected the same. Second, sensitivity of the vegetation indices evaluated for biomass estimation did not improve by orienting the sensors at a 45° angle. Third, special effort should be made to keep the sensor directly over the row while driving in the field. Vegetation index values for both sensors decreased as they moved from over the row to between the rows at V7 and displacing the sensors by 10 cm to the side of the row underestimated NDVI for the GreenSeeker sensor with corn at V10. Fourth, the red

version of the GreenSeeker provided a better estimation of biomass than the green version at V10. And finally, when using NDVI, both sensors behave essentially as biomass sensors, however N deficiency may be detected in a window ranging from V7 to V16.

Key words: Active canopy sensors, Crop Circle, GreenSeeker, reflectance, vegetation indices.

Chapter 1

Understanding how active sensors work

INTRODUCTION

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 (i.e., 400 – 700 nm) due to strong absorptance by photosynthetic and accessory plant pigments (Chappelle et al., 1992). However, the pigments involved in photosynthesis (chlorophyll) absorb visible 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, therefore, give a good indication of leaf greenness. By contrast, reflectance and transmittance are both usually high in the near-infrared (NIR) region of the spectrum (~700-1400 nm) because there is very little absorptance by subcellular particles 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, and reflectance measurements at these wavelengths provide information on the amount of living vegetation relative to the amount of uncovered soil. The color of a crop is not just determined by the color of the leaves, but is biased by the color of the soil, particularly when the crop canopy is still open.

Typically, plants with increased levels of N availability have greater leaf N concentrations, more chlorophyll (Inada, 1965; Al-Abbas et al., 1974; Wolfe et al., 1988) and greater rates of photosynthesis (Sinclair and Horie, 1989). Leaf chlorophyll content

estimated by chlorophyll meter readings correlated with corn yield just as well as leaf N concentration (Schepers et al., 1992).

Advances in remote sensing allow us to assess spatial variation in N concentrations across cornfields. For example, several studies have shown good relationships between spectral reflectance, chlorophyll content and N status in green vegetation (Bausch and Duke, 1996; Stone et al., 1996; Blackmer et al., 1996a; Osborne et al., 2002). Recently, a conceptual model that relates remotely sensed reflectance with pigment content in different media (leaves, crop canopy) was developed and used for the non-destructive estimation of Chl in higher plant leaves (Gitelson et al., 2003a), LAI in maize canopies (Gitelson et al., 2003b), and Chl content in crops (Gitelson et al., 2005).

Relative techniques were developed for using a SPAD chlorophyll meter, color photography, or canopy reflectance factors in corn (Schepers et al., 1992; Blackmer et al., 1993; Blackmer et al., 1994; Blackmer et al., 1996a; Blackmer et al., 1996b; Blackmer and Schepers, 1996; Schepers et al., 1996; Shanahan et al., 2003), wheat (Stone et al., 1996, Lukina et al., 2001; Raun et al., 2002), and cotton (Bronson et al., 2003).

Using SPAD chlorophyll meters to determine the need for in-season N fertilizer applications has the advantage that the N is highly efficient, but is not practical when growers have to fertilize large areas in a short time. On the other hand, management schemes based on the plant canopy as opposed to the individual leaf measurements obtained with SPAD readings have potential for larger scale applications and direct input into variable rate fertilizer application technology (Raun et al., 2002).

The field level research cited above was conducted using passive radiometers. These instruments use solar energy as the light source and measure the reflectance.

Active sensors also measure reflected light from crops much like passive sensors. The main difference is that active sensors produce their own source of light, and therefore, are expected to be independent of time of the day (no solar zenith and azimuth angle effect) and light intensity (cloudiness conditions). Electrical circuits within the sensor are able to differentiate between the modulated portion of the reflectance and natural component that originated with sunlight. This unique feature of active sensors is why they can operate equally well under all lighting conditions. Moreover, because of the sampling intensity (0.1sec) and density (one measurement every $\sim 0.22\text{m}$ driving at 8 km hr^{-1}), their use would permit, if tied to a GPS, a detailed map of Chl content distribution in crop fields. However some limitations associated with active sensors are 1) their extremely high sensitivity to distance to the target that affects reflectance, 2) their low energy when compared with sunlight, which may affect the number of layers penetrated and in turn total reflectance, and 3) the field of view and the rate at which each sensor acquires information also varies among commercially available active sensors. Because distance between the sun and the crop is constant for a given moment, the down welling irradiance (emitted and that reaches the object) is constant for the sun (for a given solar angle, barring no changes in cloudiness conditions). However for active sensors even if the energy emitted is constant, both emitted light and reflected light from the leaves follow the inverse square of the distance law. In that way, reflectance measured with an active sensor will decrease as distance between the sensor and target increases. These two characteristics may lead to erroneous interpretations of the results if we use single band information, and could affect the behavior of traditional vegetation indices. For example, when working with satellites and airborne imagery the impact of a little variation in

distance between source and receiver is not important. However, if we are thinking of working with tractor or pivot mounted sensors that run into a uneven or bumpy field and/or across different soil productivity zones with consequent variation in crop height, oscillations around 10 cm in canopy height and or oscillations in sensor height are expected. We need to identify whether a low value is due to low crop vigor or variations in sensor outputs. Furthermore, and especially in row crops such as corn, early in the season with low vegetation fraction, failure to keep the sensor directly over the row can cause the sensors to see only soil or different proportions of soil and crop.

We envision a system where active canopy sensors are mounted in a high clearance vehicle and interfaced to a variable rate applicator for on-the-go monitoring and delivery of N to cornfields. Understanding how active sensors work and how their output is influenced by issues like distance to canopy, orientation and position over the row, and canopy depth are crucial in developing a crop reflectance-based strategy for N management.

The present chapter summarizes results from a series of experiments conducted to answer relevant questions related to active sensor operational issues. Experiments 1, 2, and 3 were conducted to find the best position and orientation over the canopy throughout the season, and to determine output stability in a variable distance from the sensor to the canopy. Experiment 4 tested how vegetation indices varied with corn biomass and N status as affected by canopy depth.

MATERIALS AND METHODS

Sensors description

Active sensors work by using diodes to generate modulated light (pulsed at ~40,000Hz) in specific wavebands that are sensitive to plant properties of interest (e.g. chlorophyll, biomass). The Crop Circle sensor (ACS-210, Holland Scientific) simultaneously emits in two bands (visible and NIR) and has a field of view of 32 degrees by 6 degrees. The version of the sensor used in these experiments emits in amber (590nm +/-5.5nm) and NIR (880nm +/-10nm) wavebands from an array of LEDs and the light reflected is collected by companion detectors (one is filtered to reject NIR light and the other to reject visible wavebands). The sensor was calibrated using a 20% universal reflectance panel with the sensor placed in the nadir position above the panel. Sensor amplifiers for each waveband were adjusted in the factory so that a value of 1.0 was obtained from the 20% reflectance panel at 90 cm from the target. Readings are collected at ten times per second, so each recorded value is the average of about 4000 readings. Outputs of the sensor are pseudo-reflectance values for each band that allows calculation of various vegetation indices.

The GreenSeeker (Hand-held unit Model 505, NTech Industries) sensor measures incident and reflected light from the plant at $660 \pm 15\text{nm}$ (red version) and $770 \pm 15\text{ nm}$ (NIR). The green version of the sensor measures at $530 \pm 15\text{ nm}$ and $770 \pm 15\text{ nm}$ (NIR). In this case, energy is emitted from separate 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). All reflected radiation is measured

by one detector. 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).

Experiment 1: The effect of distance between the sensor and target on sensor output was tested for GreenSeeker and Crop Circle sensors. Sensors were mounted on a motorized track (screw-type garage door opener) to systematically move the sensors at a constant speed over the target. The rail was suspended perpendicular to the soil surface. Readings were taken over bare soil, turf grass, and corn at V4 and V10 growth stages (Ritchie et al., 1986) starting 40 cm above the target. This selection of targets provided a realistic range of reflectance and vegetation cover. Sensor outputs were plotted against distance to an imaginary horizontal plane located at the on top of the canopy for corn and grass and at ground level in the case of bare soil.

Experiment 2: The objective of this experiment was to evaluate the effect of sensor orientation (nadir position and 45 degree to the normal) on assessment of corn biomass. The Crop Circle sensor was tested at the Kansas River Valley Experimental Field near Topeka in June 2004 with the sensor mounted on a front-end loader tractor that made adjustments for distance above the canopy convenient. Eight field strips 180-m long with different N rates applied during the fall and at planting were sensed at V10. Average plant height (measured as a distance from the soil to a horizontal imaginary

plane on top of the canopy) was used to estimate plant biomass. Green and red versions of GreenSeeker sensor were tested in Argentina at EEA-INTA Paraná during February 2004. Sensors were mounted on a four-wheeled mobile device (moved manually) that facilitated quick changes in sensor orientation. Twenty-four plots from an on-going study with different N rates and planting densities were used to test the sensors at the V9-10 growth stage. Two linear meters of row were harvested, dried and weighed to determine dry matter. In both locations, for the nadir position, sensors were placed at a constant height of 90 cm over a horizontal imaginary plane at the top of the canopy. For the off-nadir position, the sensors were oriented at a 45 degree angle of inclination with respect to the ground and kept at a constant distance of 90 cm to the center of the plant whorl. Sensor outputs were averaged to obtain a single vegetation index value per plot (Paraná) or strip (Kansas).

Experiment 3: The objective of this experiment was to understand how corn biomass estimation is affected by sensor position over corn rows. Sensors were mounted on a modified garage door opener to systematically move the sensor across three adjacent rows. The device was placed across the rows so that the field of view was perpendicular to the row. Corn was sensed at V7 and V12.

Experiment 4: In this experiment we tested how vegetation indices varied with corn biomass and N status as affected by canopy depth. Sensor measurements were collected in the greenhouse at V7 and V12 under variable N availability conditions as well as in the field at V16. Different canopy depths were generated artificially by

systematically removing layers of leaves from the top, downward, or bottom upward. Biomass profiles were determined by destructive sampling.

Greenhouse experiment

Plant and soil material

To generate a degree of N availability, soil was mixed with sand in equal proportions (50% + 50%) and wheat straw was added at rates of 100g/pot (N₁), 75g/pot (N₂), 50 g/pot (N₃), 25 g/pot (N₄), and 0 (N₅) g/pot. Per treatment, six pots 0.26 m in diameter and 0.26 m tall were planted to corn (Pioneer hybrid 3168) on March 11th 2005 at a rate of two plants per pot with a distance of 0.15 m between them. Pots were watered daily and fertilizer was applied three times during the experiment as follows: 25 days after planting (DAP) with 228mg N/pot, 175 mg P/pot, 1257 mg K/pot, and 73 mg S/pot; 40 DAP with 228 mg N/pot and 60 DAP with 450 mg N/pot.

Data collection

Data were collected 47 DAP (V6-7 growth stage) on three pots corresponding to N₂ and N₄, herein called low and high N respectively. Twenty days later (V12 growth stage), measurements were taken on pots corresponding to N₁ and N₅. Three pots were arranged contiguously to simulate a meter of row with distance between plants of 15cm. The sensors were mounted in a motorized screw-type garage door opener to systematically move them at a constant speed, and placed at 0.8 m above the top of the canopy for the Crop Circle and 0.9 m for the GreenSeeker. Three consecutive readings were taken at each defoliation level and considered a replication for analysis purposes. Different canopy depths were generated artificially by systematically removing layers of leaves from the top, downward (three pots or 6 plants), or bottom upward (another three

pots). Leaves removed were oven dried and dry matter determined for each level of defoliation.

Field data

On July 15, 2005 corresponding with the V16 growth stage, data were collected on an ongoing study at Shelton, NE on plots that receive either 0 N/ha or 240 N/ha at V4 growth stage. Three plots per N level were measured and each plot was considered a replication. The sensors were placed and data collection proceeded in the same way as in the greenhouse.

RESULTS

Experiment 1: Pseudo NIR reflectance at 1.0 m was from 2.2 (bare soil) to 7 (grass) times higher than pseudo reflectance for the amber waveband. Values from individual bands decreased as the distance between the sensor and target increased following the inverse square law (Figure 1a and 1b). Our suggestion for the ACS-210 sensor is to work in the range between 60 and 110 cm above the canopy. Positioning the sensor closer than 60 cm significantly increases the dependence on distance. Sensor output declined from ~70% at 110 cm to only ~15% at 150 cm, compared to 60 cm.

As mentioned above, the ACS-210 was calibrated with a 20% universal reflectance panel at a distance of 90 cm from the sensor (sensor output = 1.0 with 20% panel). An NIR pseudo reflectance value of 8 for grass at 40 cm (Figure 1b) corresponds to a reflectance value of 160%, which is clearly unreasonable but illustrates the sensitivity of active sensors to distance from the target. The reality of the situation is that both NIR and red reflectance increase as distance between the sensor and canopy decreases. Vegetation indices like NDVI and reflectance ratios were developed for

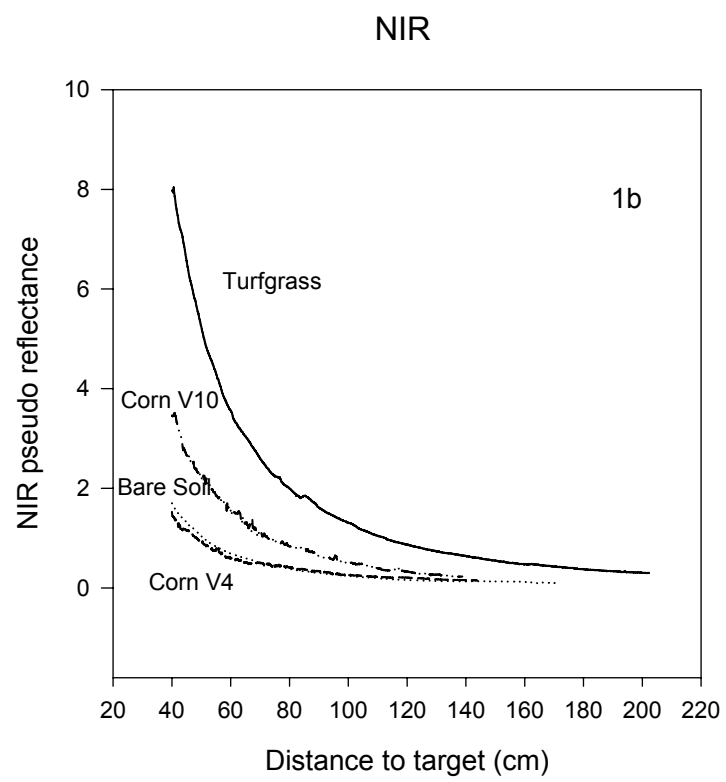
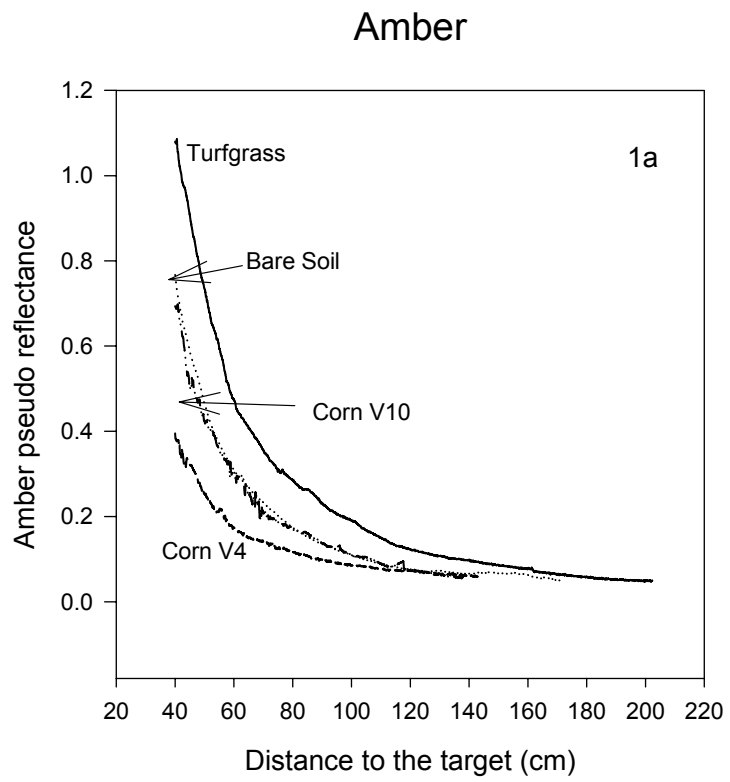


Figure 1a and 1b: NIR and amber upwelling radiance as a function of distance between Crop Circle sensor and four different targets.

passive aircraft sensor systems to compensate for atmospheric interferences. Under these conditions, distance between the sensor and target is infinitely large. However, when the sensor is moved to within a meter of the target and the energy source is weak (i.e., modulated visible and NIR radiation), distance becomes important and atmospheric interference becomes negligible. The situation with active sensors is that it does not take very much vegetation to absorb all of the red light emitted. As such, fluctuations in visible light reflectance are much more likely to be caused by changes in the distance between the sensor and target than by changes in chlorophyll status. Failure of modulated visible light to conform to reflectance concepts established for natural light (i.e., red reflectance decreases as NIR reflectance increases) raises questions about using established reflectance indices to interpret active sensor data. Figures 2a and 2b illustrate how increased distance between the sensor and target decreases the Amber ratio (NIR/amber) and ANDVI values. Based on these results, a reasonable distance window for both sensors is probably between 80-110 cm.

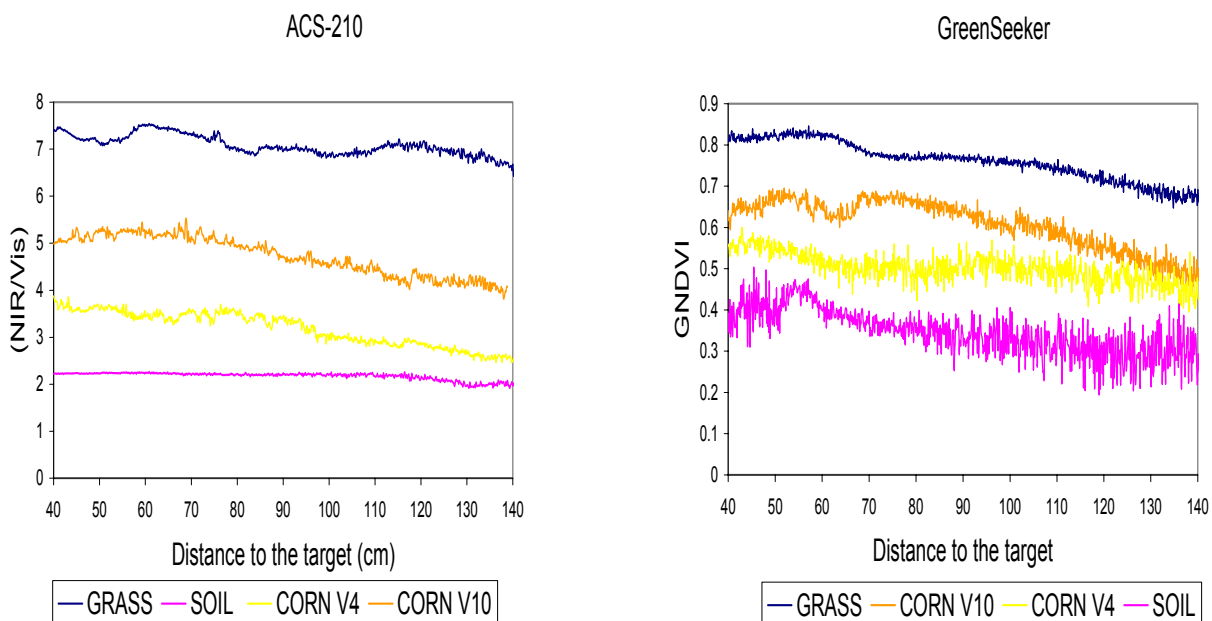


Figure 2a and 2b: Simple NIR/Amber ratio for Crop Circle sensor and green NDVI for GreenSeeker sensor as influenced by distance from sensor.

Experiment 2: It was not possible to directly compare Crop Circle and GreenSeeker sensors at both locations because the Crop Circle sensor was not available in Argentina and the GreenSeeker sensor was not functioning properly in Kansas. Better estimates of biomass were achieved using the red than the green GreenSeeker sensor at V10 (Figure 3). However, red NDVI showed less response to dry matter values $>200 \text{ g/m}^2$. This is because the vegetation was more than adequate to absorb all of the modulated red light (Myneni, 1997; Gitelson, 2004). It is not known if the NIR detector became saturated at high biomass values or the NDVI formula limited expression of the biomass (GreenSeeker software would have to be modified to provide reflectance data for individual wavebands). Both the Amber ratio (NIR/Vis) and ANDVI for the ACS-210

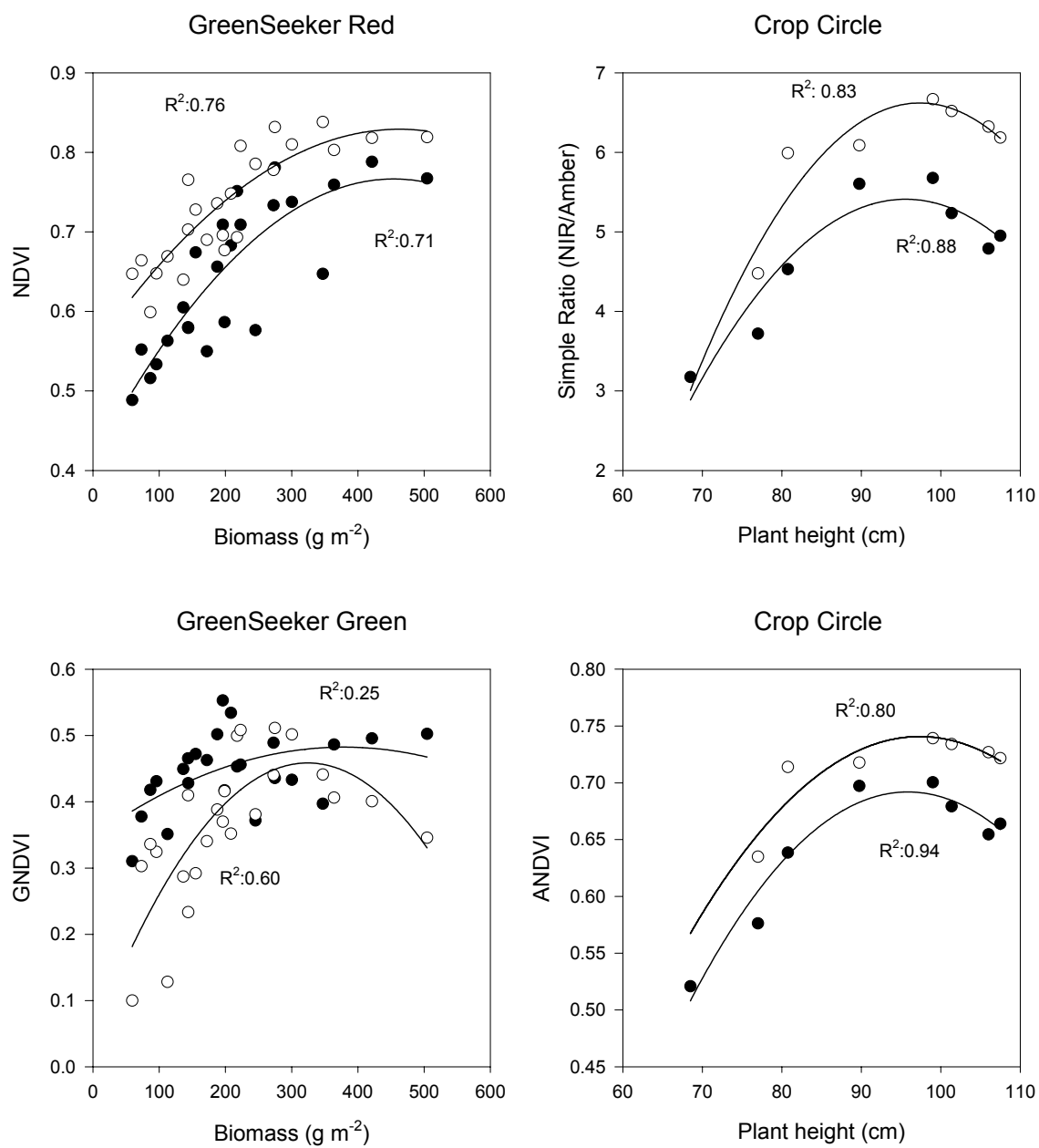


Figure 3: Sensor orientation effect on assessment of biomass. Open symbols: 45 degrees, closed symbols: nadir.

sensor were responsive to plant height at V10 (Figure 3). However, both indices saturated at relatively high biomass and/or height values at this growth stage. There was no apparent benefit to off-nadir viewing of the canopy at V10. Sensitivity of NDVI to NIR reflectance is dependent upon the NIR/Vis ratio, decreasing with an increase in the ratio (Gitelson, 2004). Even if the coefficient of determination increases in some cases by orienting the sensor with a 45-degree angle, sensitivity of NDVI and Amber ratio decreases. The main effect of placing the sensor in an off-nadir position is that the sensor “sees” more green vegetation. In that way, NIR increases and reflectance in the visible decreases, making the ratio larger and NDVI less sensitive to biomass. The situation would likely be different both at earlier growth stages (less biomass) and after tassel formation in that either the sensor height above the soil would have to be increased or the reflectance of the tassel would have a large effect on the readings. Targeting the desired portion of the canopy became an apparent problem with the green version of the GreenSeeker even though it was mounted identically to the red GreenSeeker (Figure 3). These differences could be due to the non-uniform distribution of light across the field of view and differences in the energy level between the red and green version of the sensors.

Experiment 3: The amount of biomass in the sensor’s field of view is naturally influenced by sensor location over the row. Direction of leaf orientation (plant rotation) relative to row direction can have a strong influence on sensor response (Figure 4). The lack of uniformity in response as the sensor moved across the rows was expected because the sensor was positioned to pass directly over the plant in the left row, but for the center and right rows the field of view included more inter-plant space (area between plants in

the same row) and perhaps some vegetation from adjacent plants. Individual waveband data clearly illustrate that vegetation index values for active sensors are almost entirely driven by NIR reflectance, which is highly influenced by distance between the sensor and canopy and the amount of biomass in the field of view. In a practical sense, it follows that corn is a difficult crop to monitor because leaves exist at multiple levels (thereby affecting distance to the sensor) and leaf orientation (plant rotation relative to row direction) is variable relative to the sensor's field of view.

ACS-210

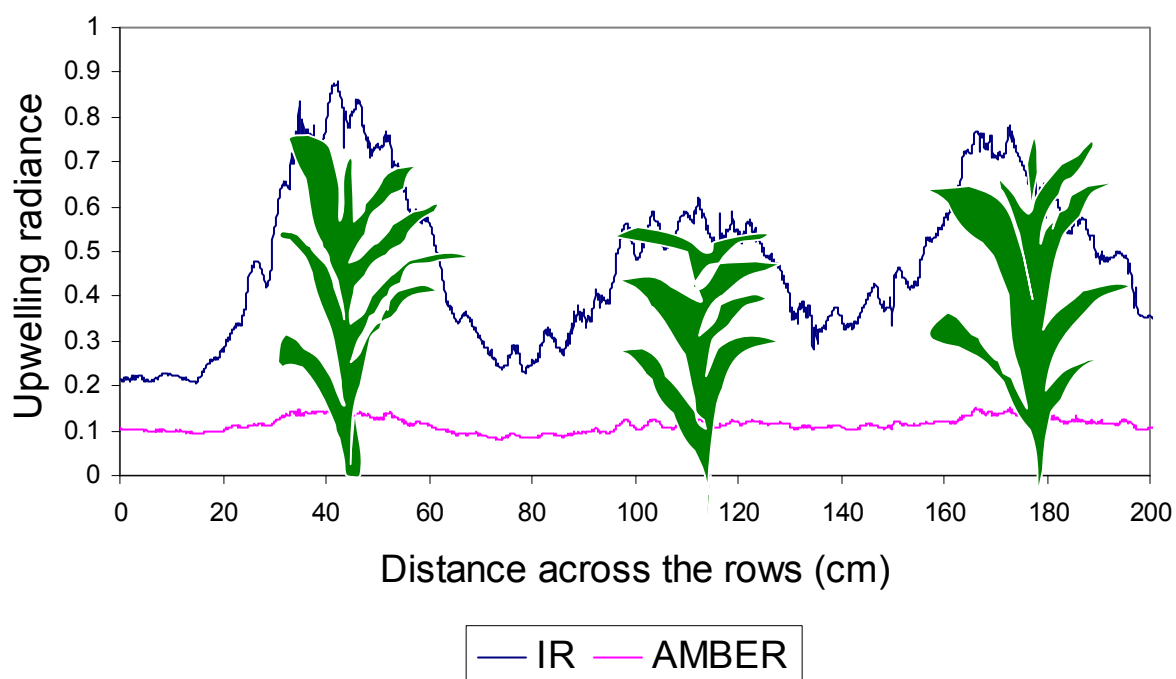


Figure 4: Individual band reflectance values as a function of distance for the Crop Circle sensor traversing over three rows of corn (long axis of sensor field of view perpendicular to row direction).

Values of vegetation indices (VI) for both sensors decrease linearly as the sensors moves laterally from top of the row with corn at V7 (ACS-210, $R^2=0.94$; GreenSeeker, $R^2=0.94$; Figure 5 a and b), mainly explained by a sharper decrease in NIR reflectance than in the amber (Figure 4). We measured a dark green corn crop, which basically means that most of the limited amount of amber radiation was absorbed by chlorophyll. Considering the following model, total reflectance from a single leaf can be calculated as Asrar et al.(1989):

$$\rho_{Tot} = \rho_{leaf} + T^2 \rho_{background} \quad [1]$$

Where ρ_{Tot} is the total reflectance, ρ_{leaf} is the reflectance of a leaf, T is transmittance of the leaf, and $\rho_{background}$ is the reflectance of the background.

The amber reflectance of the plants over a dark soil (Hord silt loam) slightly decreases as the number of layers (leaves) decreases because most of the radiation is absorbed in the first layer of leaves. By adding successive leaves to the plant (moving towards the row) the contribution of the reflectance of the second, third and successive layers are very small due to two effects: a) low reflectance of a leaf of similar spectral characteristics, and b) low transmittance (smaller than one and rose to an increasing power as the number of layers increased) and multiplying reflectance of the background, so the effect is to diminish the effect of reflectance of the background. In addition, notice the similarities in amber reflectance for corn at V10 and bare soil (figure 1b). Conversely, in the NIR waveband, reflectance increases as the number of layers increases because NIR penetrates the canopy and there is an effective contribution of successive layers to total reflectance.

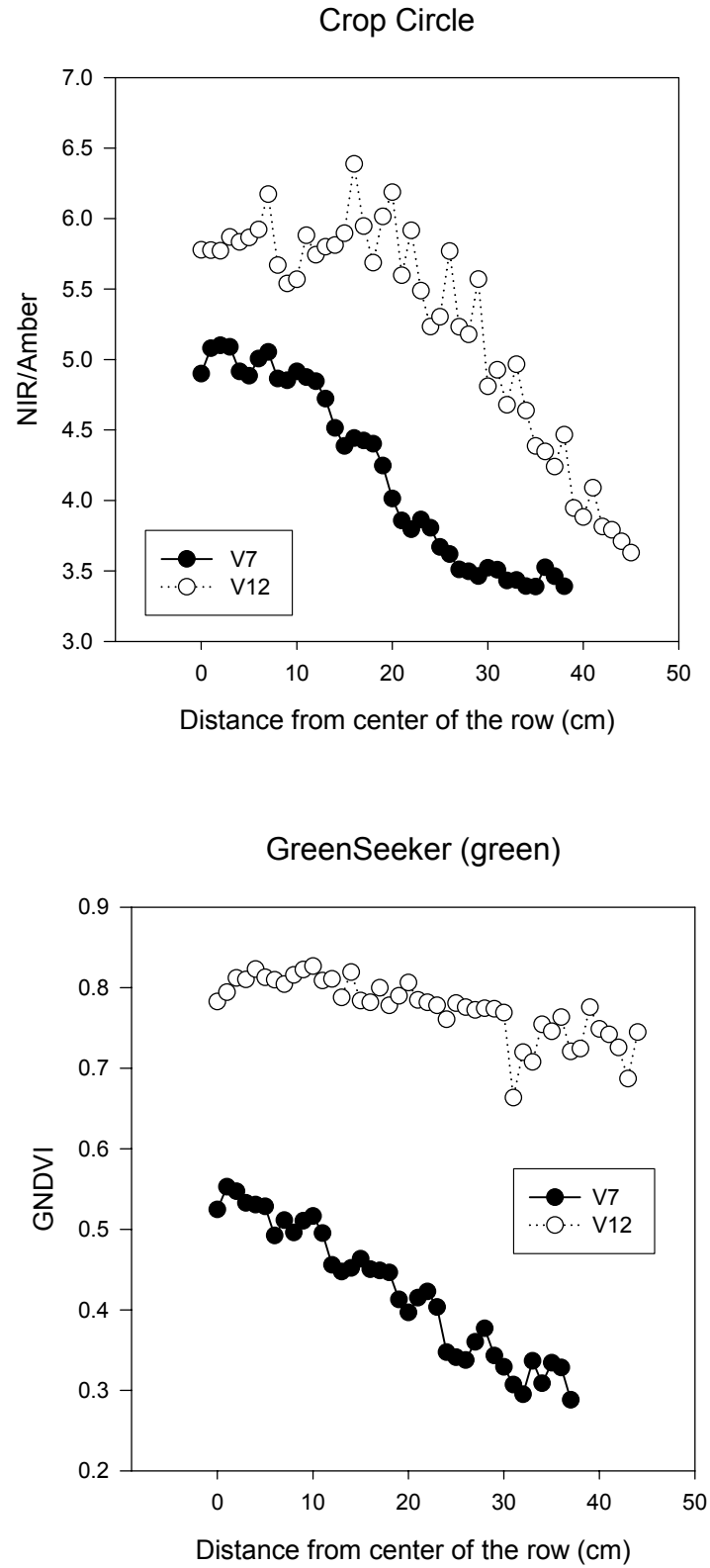


Figure 5: Declining of vegetation indices as sensor moves away from the center of the row.

It is worth noting that slope for VI decrease is a function of row width and canopy closure. As the canopy growth and soil cover increases the effect of the row became less important (Figure 5a and 5b). A completely closed corn canopy behaves as an optically deep medium, which means that an increase in thickness results in no noticeable difference in the measured reflectance. As the thickness of the medium increases transmittance decreases. In that way reflectance of the background reduces its contribution to total reflectance.

To illustrate the integrated effect of not positioning the sensor directly over the row, we placed the sensors at 90 cm over the canopy and moved them laterally 10-15 cm from the center of the row. Readings were collected while moving through the field with the sensors mounted on a tractor with a front-end loader (Kansas) or on a mobile device (Argentina). In the case of the GreenSeeker, a sensor offset of 10-15 cm clearly underestimated the NDVI values for corn at V10 (Figure 6). These data illustrate the importance of keeping the GreenSeeker positioned directly over the plant row (i.e., GNDVI consistently lower for the offset position). This point is attributed to the fact that light intensity is not uniformly distributed across the field of view with the GreenSeeker (e.g., ~75% of the radiation is concentrated in the center 25-30 cm of the 60 cm width of the field of view). In the case of the Crop Circle sensor, half of the data points showed that the offset sensor position had no effect on sensor output. The remaining half suggests a possible offset effect.

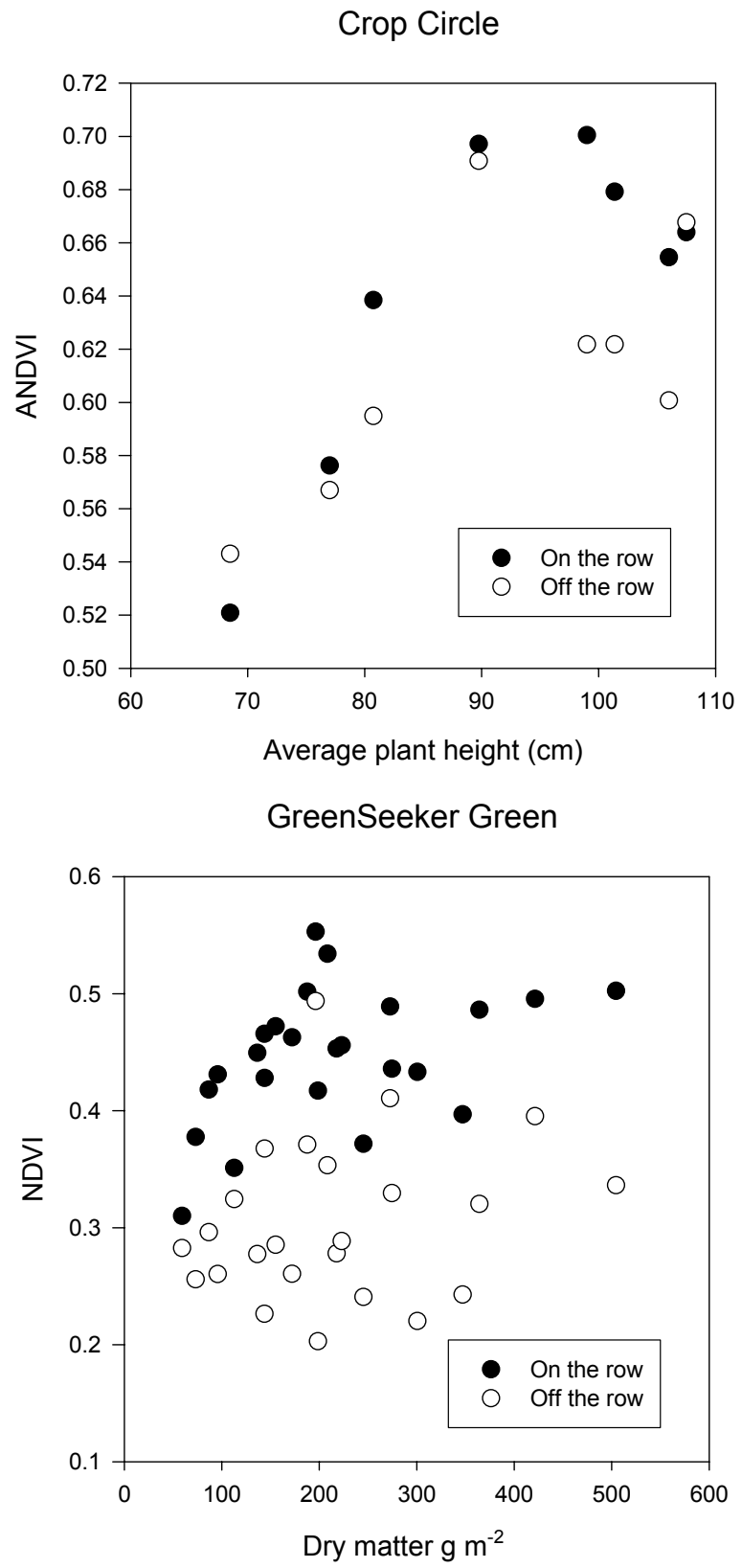


Figure 6: Comparison between sensor outputs when placed in the nadir position over the row vs. 10-15 cm to the side of the row.

Experiment 4: Results from the greenhouse experiment showed that at V7 and V12 NDVI values differed between sensors (different bands), and between N levels. As expected, NDVI values were higher for high N availability levels. NDVI values were affected by canopy depth for both sensors. In general, the variability of the outputs for a given target was lower for the Crop Circle sensor than for the GreenSeeker sensor (Figure 7a,b,c,d). These results were confirmed when six consecutive readings were taken over the same portion of a row at V12 using both sensors (Figure 8 a and b). Particular characteristics of each sensor such as pulse rate, field of view, light source and detectors may help to understand such differences.

Effect of pulse rate and field of view

Because sensor readings are taken so frequently, everything within the field of view will be monitored with a high degree of spatial resolution. For example, traveling at 6.4 km h^{-1} , the field of view advances at the rate of 0.0447 mm per reading. Assuming that these readings are accumulated and outputted every 0.1 second, this means that a new value is recorded every 0.178 m. Higher speeds increase the distance traveled between reported data points proportionately. However, while moving through a field, the value from one reading to the next should be similar because reflectance for the current frame (field of view) has only changed minimally from the last frame (i.e., minus a small area on the back side, plus the same area on the leading side).

In the case of the GreenSeeker sensor, the field of view advances by about 0.7% every time a new reading is taken, assuming about a 1 by 60 cm field of view. In the case of the Crop Circle sensor, the field of view is about 10 cm by 60 cm at 90 cm from the target, so every time a reading is taken the footprint advances about 0.18% in the

Crop Circle

GreenSeeker

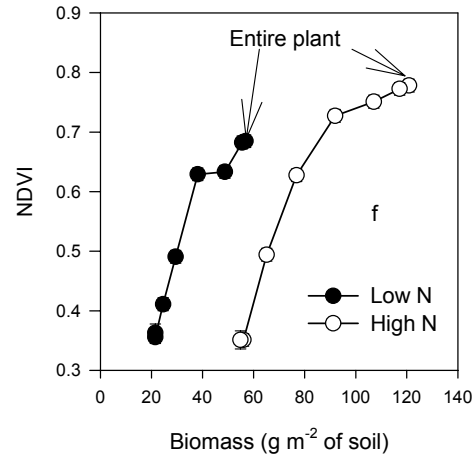
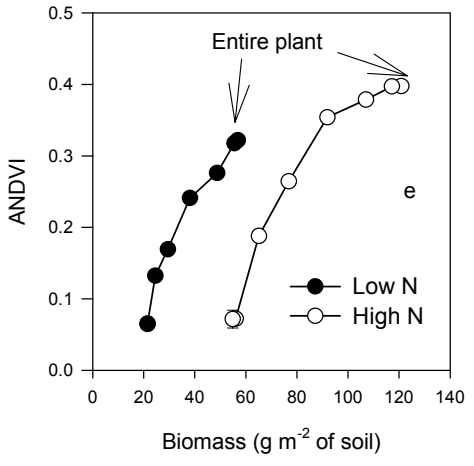
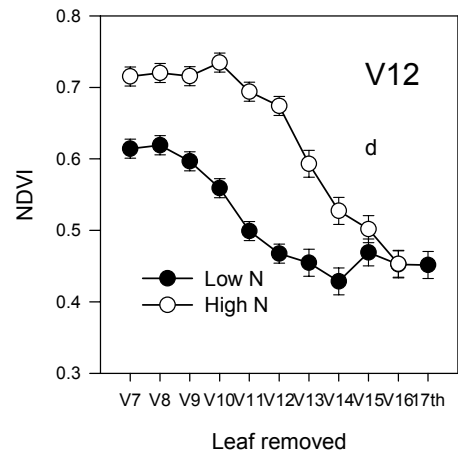
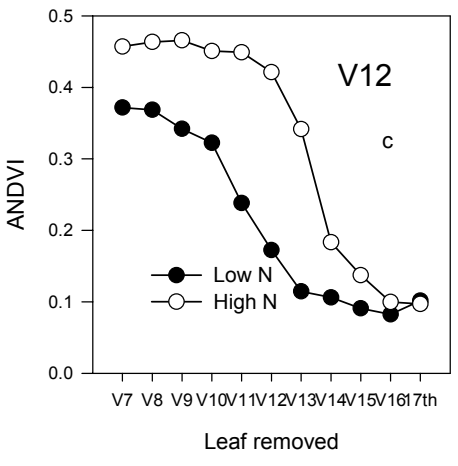
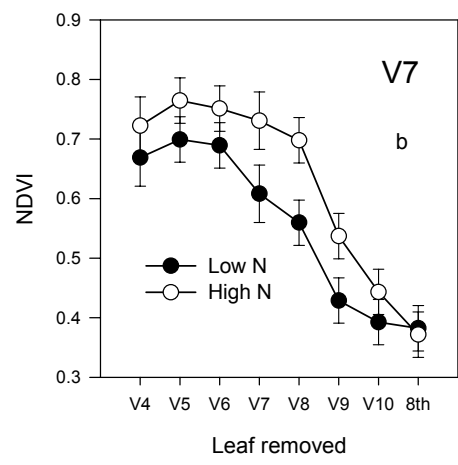
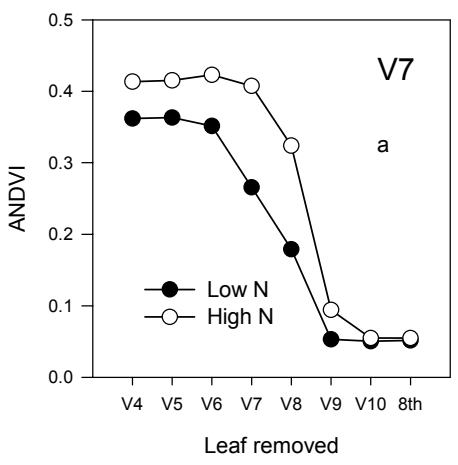


Figure 7: Effect of leaf removal from bottom upward (a, b, c, and d), and top

down (e, f) on VI values for two sensors under two N levels and a t two growth stages.

direction of travel at 6.4 km h^{-1} . This illustrates that if readings were taken at a rate of 40,000 samples per second, one should not expect much difference from one reading to the next if the electronics are stable.

Effect of light source

In the case of the GreenSeeker sensor, energy is emitted from separate 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). All reflected radiation is measured by one detector, so the quality of the detector's electronics dictates if the detector circuits are able to accurately capture a low level of reflectance for the visible waveband and then instantaneously respond to a high reflectance level for the NIR waveband. During the 40 pulses from a given diode source, the sensor advances 1.788 mm or about 3% of its field of view at 6.4 km h^{-1} . Or in other words, the reflectance for one waveband is only 97% of the area recorded by the companion waveband. At 13 km h^{-1} the concurrence reduces to 94% and at 25 km h^{-1} to only 88%. The implications are that the targets for which subsequent calculations are made are not the same and users should expect greater variability in sensor readings at higher speeds. Output variability attributed to speed of the monitoring vehicle might be confounded by other sources or variability, which is why it is important to record the variability in sensor output for 15 sec or so (~ 150 points) in a stationary position over a crop target to better appreciate the quality of the data.

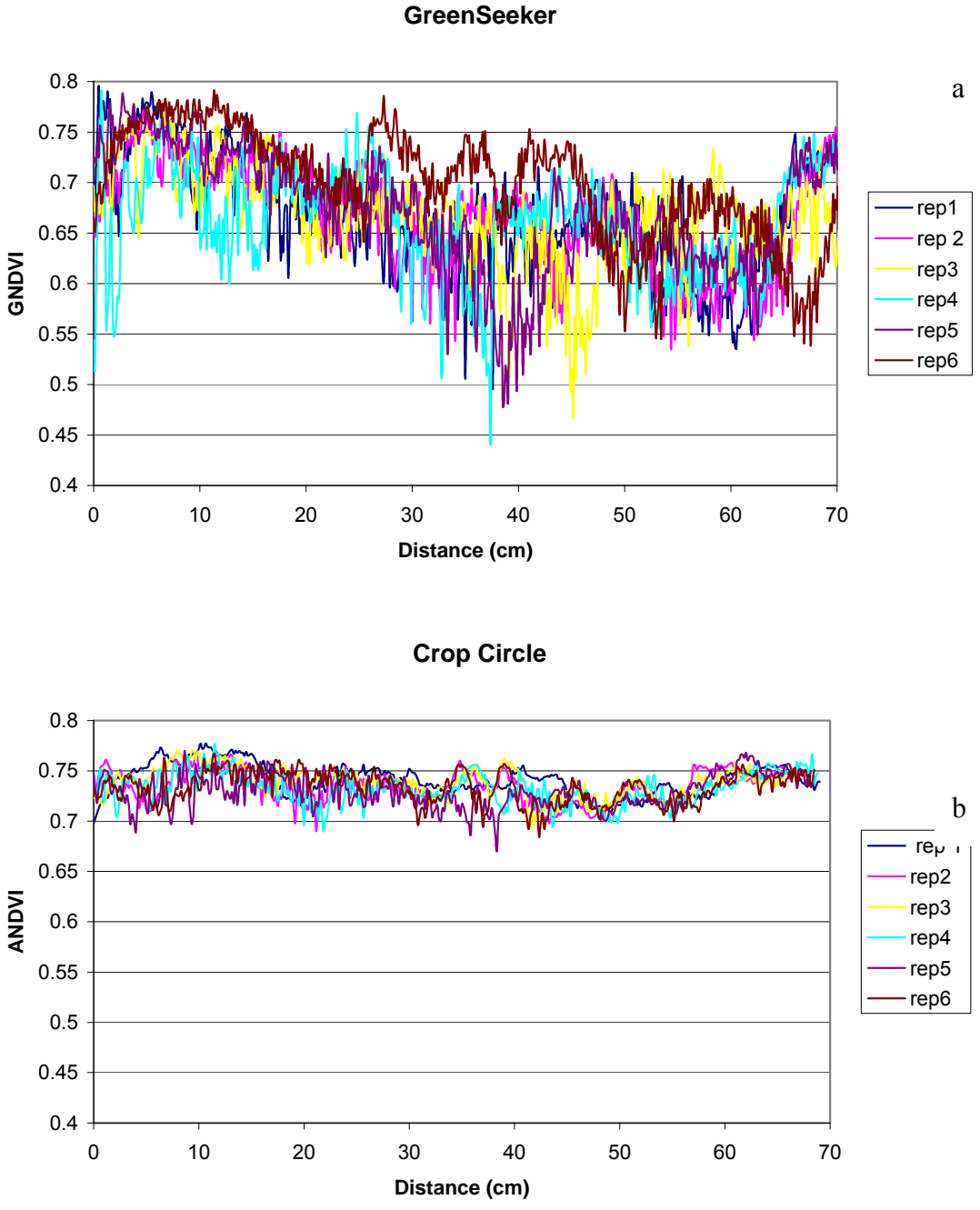


Figure 8: Variability in VI outputs for GreenSeeker (a), and Crop Circle (b). Six consecutive readings were collected over the same portion of a cornrow at V12.

In the case of Crop Circle, both wavebands are projected simultaneously from the same diode so the field of view is identical with each pulse of light. Therefore, the same exact area of the target is illuminated for an instant and reflectance from that area is recorded by a separate detector for each waveband. As such, detector hysteresis is less problematic and eliminating the need to alternate radiation sources allows for higher sampling rates to be achieved.

ANDVI values from the Crop Circle sensor did not respond to leaf removal from the bottom upwards until the uppermost-expanded leaf was detached in the case of high N plants. Under low N conditions (also smaller plants), ANDVI values were responsive starting one leaf below the uppermost expanded. For GreenSeeker, however, NDVI values from the uppermost-expanded leaf and the leaf immediately above were not different (Figures 7 b and d).

When leaves were removed from the top down ANDVI and NDVI were proportionate to the biomass in the field of view (Figures 7 e, and f). Active sensors do not generate enough light to measure very deep into the canopy, so in the case of corn they usually become saturated in terms of near infrared (NIR) reflectance once 5 to 6 layers of leaves develop. The experiment was repeated in the field with the Crop Circle sensor and similar results were found (Figure 9a and b).

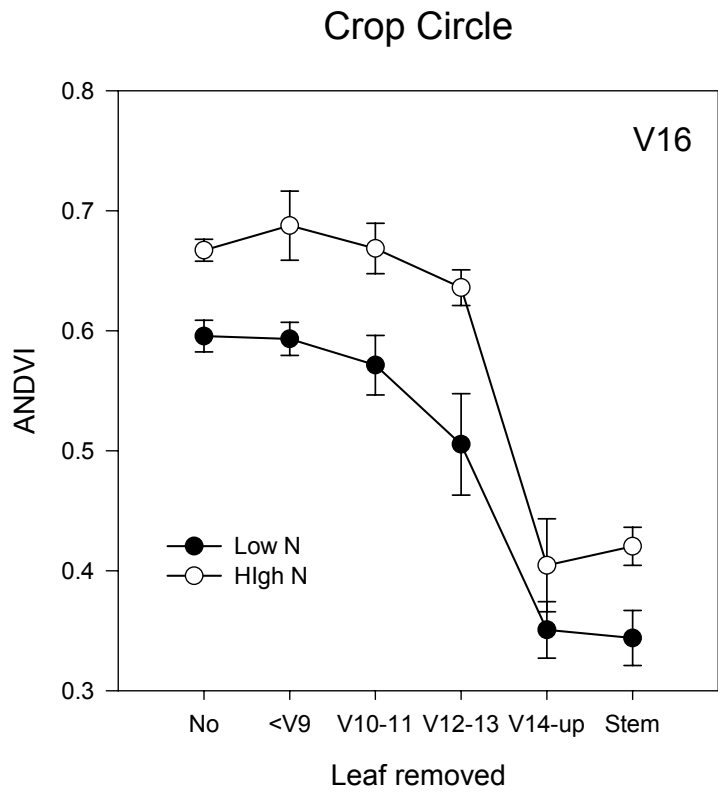
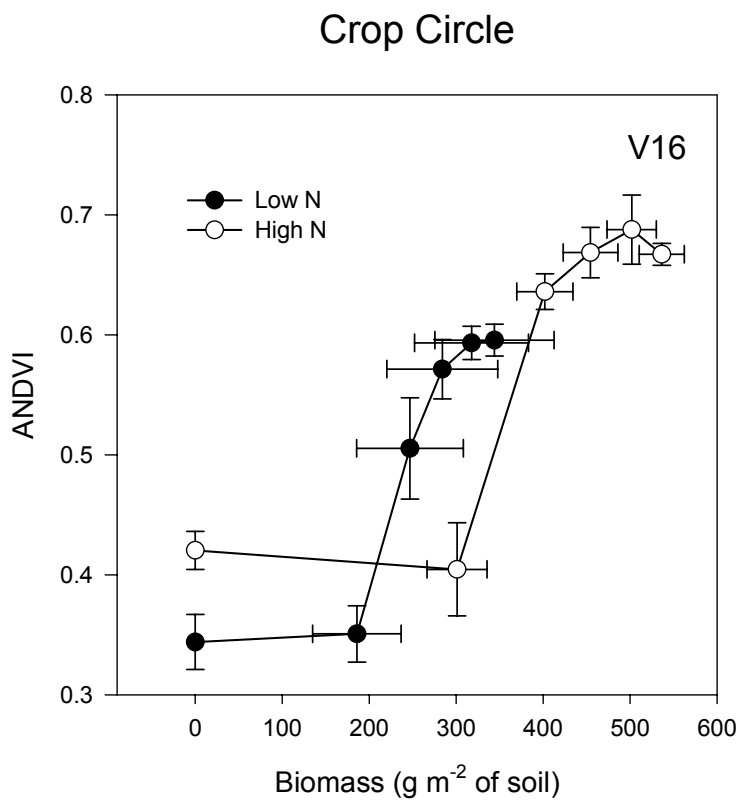


Figure 9: Effect of leaf removal on VI values from the Crop Circle sensor under two levels at V16.

SUMMARY AND CONCLUSION

The effect of sensor positioning and orientation over the canopy and their effects on assessment of biomass and N status were tested using two different active canopy sensors, Crop Circle and GreenSeeker. Fundamental information was retrieved from these experiments. First, sensitivity prompted us to work between 60 and 110 cm over the canopy with the Crop Circle sensor and between 80 and 110 cm for the GreenSeeker sensor. It is important to note that vegetation indices involving a ratio of reflectance values (i.e. NIR/amber) are largely immune to the effect of distance between the sensor and target, but reflectance data from the individual bands are not. Therefore, variability in data from the NIR band for example, can be due to either distance between the sensor and top of the canopy or the amount of living vegetation in the field of view. Normalizing data from several bands removes the effect of distance because both are affected the same. Second, sensitivity of the vegetation indices evaluated for biomass estimation did not improve by orienting the sensors at a 45° angle at the V10 growth stage. Further test should be conducted to confirm these findings at earlier growth stages. Third, special effort should be made to keep the sensor directly over the row while driving in the field. Vegetation index values for both sensors decreased as they moved from over the row to between the rows at V7; and displacing the sensors by 10 cm to the side of the row underestimated NDVI for the GreenSeeker sensor with corn at V10. Fourth, the red version of the GreenSeeker provided a better estimation of biomass than the green version at V10. Finally, when using NDVI, both sensors behave essentially as biomass sensors, however N deficiency may be detected in a window ranging from V7 to V16.

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Chapter 2

Assessment of corn chlorophyll status using an active canopy sensor

ABSTRACT

Maintaining an adequate supply of nitrogen (N) throughout the life of a crop is essential to producing economically optimum yields. The need to reliably assess crop vigor and nutrient status has partially been addressed with recent advances in remote sensing (aircraft and ground-based sensors), but our ability to make nutrient recommendations based on in-season measurement of crop biomass and chlorophyll content is lacking. The objective of this experiment was to assess Chl status in cornfields using active crop canopy sensor readings by meanings of comparing the results with relative SPAD units. Sensor and SPAD readings were collected in three cornfields in central Nebraska from V9 to R4. Our results indicate that sensor readings provide information not only about relative Chl content but also about plant distribution and biomass. The four indices evaluated here were linearly related with RSPAD readings during vegetative growth stages. RWDRVI, RChl index, and RAR showed more sensitivity than RANDVI to variations in relative Chl content. Active sensor technology can be used for on-the-go assessment of N status in irrigated cornfields. More research is needed in order to validate these results in a wider range of climatic conditions.

Key words: Active sensors, chlorophyll, vegetation indices, corn, SPAD

Chapter 2

Assessment of corn chlorophyll status using an active canopy sensor

INTRODUCTION

Maintaining an adequate supply of nitrogen (N) throughout the life of a crop is essential to achieve economically optimum yields. However, making sure that there are enough nutrients to meet total crop needs at the beginning of the growing season can be risky to the environment in the case of mobile nutrients. In Nebraska, for example, over-application of nitrogen fertilizer on corn has led to elevated levels of N in ground and surface waters. Traditionally, farmers apply large amounts of N early in the season, before the crop can effectively use it (Schepers et al., 1991). This practice increased export of reactive N to downstream aquatic environments, resulting in eutrophication and, in some cases hypoxia in coastal ecosystems (CAST, 1999; Matson et al., 2002, Rabalais, 2002). The state of Nebraska was considered to contribute 11% of the N that annually reaches and contaminates the Gulf of Mexico (Maede, 1995).

Reported values of nitrogen use efficiency (NUE) average around 33% in a whole world basis (Raun and Johnson, 1999). In north-central USA under various rotations, nitrogen fertilizer-uptake efficiency by corn was reported as $37\% \pm 30\%$ (Cassman et al., 2002). Use of rotations, conservation tillage, $\text{NH}_4\text{-N}$ source, in-season applied N, precision agriculture and application resolution have being proposed among others to improve NUE (Raun and Johnson, 1999, Halvorson and Reule, 1994, Rao and Dao, 1996, Wuest and Cassman, 1992, Schepers et al, 1995, Stone et al, 1996).

The key challenge with regard to N fertilizer use is, therefore, to produce an adequate supply of food while protecting environmental quality and conserving natural resources for future generations. Agronomic actions are needed to improve fertilizer management and overall N use efficiency because global food security cannot be achieved without meeting the increasing N requirements of crop production (Smil, 1997; Cassman et al., 2003).

Many efforts have been made in this direction. In the majority, approaches have been based on soil processes. In fact, and even though they vary widely among states, current fertilizer recommendations in the Corn Belt are based on soil indicators. Some include yield goal (Nebraska, Kansas, Colorado, and Minnesota), soil organic matter content (Nebraska, Kansas, Colorado, Minnesota), residual soil nitrate-nitrogen content (Nebraska, Kansas, Colorado, Minnesota) and credits for nitrogen from legumes, manure, and irrigation water (see table 4 in Dobermann and Cassman, 2002).

The use of a soil-based management zones (MZ) approach has been proposed as a means to direct variable N application rates to better match N supply with landscape spatial variation in crop N requirements. However, evidence has accumulated suggesting that the MZ approach alone will not be completely effective in making accurate variable N applications, given the large effect temporal variation in Corn Belt climate has on expression of spatial variation in soil N supply and crop N needs (Jaynes and Colvin, 1997; Ferguson et al., 2002; Eghball et al., 2003; Dobermann et al., 2003; Schepers et al., 2004).

An alternative or maybe complimentary approach is to use plants and crops as indicators of site conditions. Plants and crops are good indicators of environmental status

since they integrate the cumulative effect of weather and management practices over the season. Typically, plants with increased levels of N availability have greater leaf N concentrations, more chlorophyll (Inada, 1965; Al-Abbas et al, 1974; Wolfe et al, 1988) and greater rates of photosynthesis (Sinclair and Horie, 1989). Leaf chlorophyll content estimated by chlorophyll meter readings correlated with corn yield just as well as leaf N concentration (Schepers et al., 1992).

A crop-based N management strategy should identify crop N needs and provide N in the amount required to maintain or improve yields while reducing environmental impacts. Relative techniques were developed for using a SPAD chlorophyll meter, color photography, or canopy reflectance factors to assess spatial variation in N concentrations across growers' cornfields (Schepers et al., 1992; Blackmer et al., 1993; Blackmer et al., 1994; Blackmer and Schepers, 1994; Blackmer et al., 1996a; Blackmer et al., 1996b; Schepers et al., 1996). Furthermore, several studies have shown good relationships between spectral reflectance, chlorophyll content and N status in green vegetation (Bausch and Duke, 1996; Stone et al., 1996; Blackmer et al., 1996a; Ma et al., 1996; Osborne et al., 2002, Gitelson et al., 2005). The concept of "spoon feeding" N to the crop on an "as needed" basis (Schepers et al., 1995) is intended to reduce the potential for environmental contamination by N in corn production. This strategy is based on results obtained using the SPAD chlorophyll meter to monitor crop N status and applying fertilizer N as needed, via fertigation (injecting fertilizer into irrigation water). A sufficiency index of 0.92 to 0.95 using SPAD meters is considered indicative of N sufficiency (Blackmer and Schepers, 1995, Piekielek et al., 1995, Bausch and Duke, 1996, Jemison and Lytle, 1996; Waskom et al., 1996; Sunderman et al., 1997; Varvel et

al., 1997). Using this “spoon feeding” technique from V8 (Ritchie et al., 1992) to R1 and a threshold value of 0.95, Varvel et al. (1997) were able to maintain crop yield with less N fertilizer compared to a uniform rate of 200 kg ha⁻¹. Sawyer et al. (2004) found that a sufficiency index of 0.97 corresponded to a differential of zero from economic optimum for corn growing in Iowa. This strategy has the great advantage that is highly efficient in N use, but is not practical when growers have to fertilize a great number of corn hectares in rainfed conditions, and is highly fuel and time demanding. A recent study using canopy sensors and the nitrogen response index to monitor in-season plant N resulted in reducing applied N (Bausch and Diker, 2001). Because this index was based on the plant canopy as opposed to the individual leaf measurements obtained with the SPAD readings, it has potential for larger scale applications and direct input into variable rate fertilizer application technology. In the same way, Shanahan et al., (2003) found that GreenNDVI (Gitelson et al., 1996) was well correlated with SPAD readings for corn at V11 and could be used for on- the- go N corrections.

Active canopy sensors produce their own source of light, and therefore, are independent of time of day (no solar azimuth angle effect) and cloudiness conditions. Moreover, because of the sampling density, (one measurement every ~ 0.22m driving at 8 km hr⁻¹) their use would permit a detailed map of Chl content distribution in crop fields. However some limitations associated with active sensors’ nature are: their extreme sensitivity to distance to the target that affects reflectance, and their low energy when compared with sunlight, which affects the number of layers penetrated and in turn total reflectance. Passive sensors use solar energy as light source. Because distance between the sun and the crop is constant for a given moment, the downwelling irradiance (emitted

radiation that reach the object) is constant for the sun (for a given solar angle and no changes in cloudiness conditions). However for active sensors even if energy emitted is constant, the incident light that reaches a point is a function of distance and decreases as distance squared. Thereby, reflectance measured with an active sensor will decrease as distance between the sensor and the target increases following the inverse square law. These two characteristics can affect the behavior of traditional vegetation indices such as NDVI (Deering et al, 1975), GreenNDVI (Gitelson et al., 1996), WDRVI (Gitelson, 2004), Simple Ratio and Chl index (Gitelson et al., 2003a and 2005). These indices were developed using either passive sensors (i.e. sensors that use solar energy) or active sensors with a clip that ensures that the distance between the source of light and the target is constant. Developing an algorithm based on reflectance readings from active sensors for on-the-go N management will lead to increased NUE, decreased environmental risks, and potentially greater profits for corn growers. We hypothesized that active crop canopy sensors can be used for on- the- go measurement of relative Chl status in irrigated cornfields. The objectives of this paper were to determine 1) the most appropriate phenological growth stages, and 2) the vegetation index for maximum sensitivity in remotely sensing variation in corn canopy greenness or N status.

MATERIALS AND METHODS

Experimental Treatments and Field Design

To address our study objectives, plots were established at three separate study sites during the 2005 growing season near Shelton, NE (40.75209N, -98.766W, elevation 620 m above sea level), where N was applied in different amounts and at different times

in an attempt to generate canopies with varying N status. All three studies were conducted within the bounds of the Nebraska Management Systems Evaluation Area (MSEA) Project. Studies were designated as South linear (SL) and North linear (NL), and Niemack (NK). The soil at all three sites is a Hord silt loam (*Fine-silty, mixed mesic Pachic Haplustoll*, 0 – 1% slope). Studies were conducted on fields that had been under sprinkler irrigation with continuous corn for the last 15 years. Corn was seeded on 9 May, 2005 at the SL and NL sites and 25 April, 2005 on the NK field at a target density of 74,000 seeds ha⁻¹. To satisfy the P requirements at all sites, liquid fertilizer (10-34-0) was applied at the rate of 94 liter ha⁻¹ beneath the seed at planting, providing approximately 18 kg ha⁻¹ of P. The crop received irrigation throughout the growing season according to established irrigation scheduling principles. Weed control at all sites was accomplished through a combination of cultivation and herbicide application. Climatological data were recorded through the use of an automated weather station (High Plains Climate Center Network, University of Nebraska) located on the MSEA site. Phenology data according to Ritchie et al. (1992) were recorded weekly from 1 June through mid-August. Accumulated growing degree-days (GDD) were calculated by summing daily GDD's where $GDD = [(T_{MAX} + T_{MIN})/2] - T_{BASE}$, and T_{MAX} is the daily maximum air temperature, T_{MIN} is the daily minimum air temperature, and T_{BASE} was set as 10° C. An upper temperature threshold (T_{UT}) was set at 30° C. Before entering data into Eq. (1), T_{MAX} and T_{MIN} were set equal to T_{BASE} if less than T_{BASE} and were set equal to T_{UT} when greater than T_{UT} (McMaster and Wilhelm, 1997). The starting date for accumulating GDD was the planting date in each field.

The SL field plots were part of an ongoing study (1991- present) involving treatments consisting of a factorial combination of four hybrids and five N application levels (0, 50, 100, 150, and 200 kg N ha⁻¹). A split plot arrangement of treatments was used with hybrids as main plots and N levels as subplots with four replications in a randomized complete block design. Sensor data for this study were collected from only two of the four Pioneer brand hybrids (“P33V15”, upright canopy; “P31N27”, planophile canopy). Since hybrid and N treatments had been applied to the same areas from the beginning of the original study, residual soil N levels were low in the control plots (0 kg N ha⁻¹), and crop response to N was assured at this site. Individual plot dimensions were 7.3 by 15.2 m, consisting of eight 0.91-m rows planted in an east-west direction. Nitrogen fertilizer, as 28% UAN, was applied shortly after planting.

Treatments on NL and NK fields consisted of a combination of four N rates (0, 45, 90, and 270 kg ha⁻¹) applied at planting, and five N rates (0, 45, 90, 135, and 180 kg ha⁻¹) applied at either V11 or V15. The experimental design involved a split-split plot arrangement with three replications. Timing of N application was designated as the whole plot (V11 or V15), planting N rate was the split plot, and mid-season N application rate was the split-split plot. Plot dimensions for both sites were 7.3 by 15.2 m, consisting of 8 rows (0.91 m apart). Pioneer brand hybrid “P33G30” was planted at the NL site and “P34N42” was planted at the NK site. The N treatments were applied at the appropriate times as 28% UAN solution.

Description of Active Sensor System

The active sensor used in this work was the Crop Circle, model ACS-210, developed by Holland Scientific (<http://www.hollandscientific.com/>) through a

Cooperative Research and Development Agreement (CRADA) with USDA-ARS. The sensor operates by generating its own source of modulated light, pulsed at $\sim 40,000$ Hz, using a single polychromatic light emitting diode (LED) that simultaneously emits light in the visible (amber, $590\text{nm} \pm 5.5\text{nm}$) and near infrared (NIR) regions ($880\text{nm} \sim \pm 10\text{nm}$) of the electromagnetic spectrum. The single-diode approach results in the same exact area of the target being illuminated with each pulse of light. Reflectance of modulated light from the target area back to the sensor is measured with separate photodetectors for each waveband (Detector 1: 400nm to 680nm ; Detector 2: 800nm to 1100nm). As such, detector hysteresis is less problematic. The polychromatic light source eliminates the need to alternate radiation sources and allows for higher sampling rates to be achieved. Sensor readings were collected at ten times per second, so each recorded value represents the average of about 4000 individual sensor readings. Photodetection of ambient light by the sensor is rejected at an illumination level of up to 400 W m^{-2} . The field of view for the sensor is 32 degrees by 6 degrees. The sensor was calibrated using a 20% universal reflectance panel with the sensor placed in the nadir position above the panel. Sensor amplifiers for each waveband were adjusted so that a value of 1.0 was obtained from the 20% reflectance panel at 90 cm from the target. Final output from the sensor is a pseudo-reflectance value for each band that allows for the calculation of various vegetation indices.

Acquisition of Sensor Reflectance Data and Conversion to Vegetation Indices

Sensor readings were collected starting on 27 June, which corresponded to the V9 growth stage at SL and NL and V11 on site NK. To accomplish this, one active sensor was mounted on an adjustable height platform on a high clearance tractor that allowed for

maintenance of constant sensor distance above the target throughout the entire growing season. Sensor height was maintained at 0.8 m above the crop canopy for the plot receiving the highest N rate. Sensor readings were collected via computer as the high clearance vehicle traveled through the plots at 6 to 7 km/hr. Readings were collected with the sensor positioned over the 5th southern row in a nadir view. The sensor was interfaced with a Garmin model 16A DGPS receiver to provide spatial coordinates for all sensor readings. Data were imported into a GIS for georeferencing purposes. An area of interest (AOI) was produced for each plot that corresponded to the plot boundary minus a 1.0-m buffer area adjacent to the plot alleyways. Sensor readings were extracted from the AOI to avoid border effects in each plot. Individual sensor readings within a given plot were then averaged to produce one value for each sensor band per plot. Reflectance values from the amber and NIR bands of the sensor were in turn inputted into the four vegetation indices previously presented, substituting the amber band for the traditional color band in each equation:

$$1) \text{ (ANDVI)} = (\text{NIR} - \text{Amber}) / (\text{NIR} + \text{Amber}),$$

$$2) \text{ Amber ratio (AR)} = \text{NIR} / \text{Amber},$$

$$3) \text{ WDRVI} = (a \text{ NIR} - \text{Amber}) / (a \text{ NIR} + \text{Amber}), \text{ with } a = 0.1, \text{ and}$$

$$4) \text{ Chlorophyll index (CHLI) where } \text{CHLI} = (\text{NIR} / \text{Amber}) - 1.$$

Leaf Chlorophyll Content Assessment

Leaf chlorophyll content among treatments was assessed with the model 502 Minolta SPAD chlorophyll meter (Spectrum Technologies, Plainfield, IL) according to Blackmer and Schepers (1995) on the day of collection of crop canopy reflectance measurements. Prior to the silking growth stage, readings were collected from the most

recent fully expanded leaf (visible collar) and after silking the ear leaf was sampled. Measurements were taken midway between the leaf tip and base and midway between the margin and the midrib of the leaf from 30 representative plants selected from the center two rows of each plot, and averaged. Plants unusually close together or far apart or those that were damaged were not sampled.

Data Analysis

To account for the effect in differences among hybrids, SPAD instruments, and between growth stages, sensor and SPAD readings were normalized within replicates and hybrid for each growth stage using the highest N rate at planting as the denominator (i.e., $RANDVI = ANDVI_{plot\ i} / ANDVI_{highest\ N\ rate}$). For testing the effect of SPAD based sufficiency index (SI_{SPAD}), site and time (accumulated GDD) and their interactions on sensor based sufficiency indices (SI_{SENSOR}), each combination of site and GDD was considered a different environment because accumulated GDD were not the same for each site. A strong three-way interaction among SI_{SPAD} , site, and accumulated GDD affecting relative vegetation indices (RVIs) was found. Therefore, treatment induced variation in vegetation indices and chlorophyll meter data were assessed via analysis of variance (ANOVA) by site and GDD using a mixed model with the SAS PROC MIXED procedure (Littel et al., 1996). Hybrids and N treatments were considered fixed effects, and blocks random effects. Regression analysis was used to determine the associations between the different vegetation indices and their respective chlorophyll meter values for each growth stage and study site using PROC GLM. In addition to simple linear regression analysis, each relationship was evaluated for the presence of a quadratic component. The coefficients of determination for regression (R^2) and the root mean

square error (RMSE) were among the statistical tests utilized to evaluate the degree of association between relative chlorophyll meter readings and readings for the various vegetation indices (VIs). A comparison of slopes for the various relationships was utilized to estimate sensitivity because data normalization allows direct comparisons among different indices with different scales and dynamic ranges. Single degree of freedom comparisons were performed to test the differences among the slopes of these relationships.

RESULTS AND DISCUSSION

Average temperatures for the 2005 growing season were near the long term average for this location (Figure 1), while rainfall patterns were somewhat atypical for this location. A total of 215 mm of precipitation was received on 11 May, with 170 mm falling in a five hr period. This precipitation event led to crop emergence problems for the late-planted SL and NL sites, and resulted in of non-uniform stands at the NL site. The remainder of the season provided relatively average weather conditions, and crop yields were near normal for the SL and NK studies, where uniform stands were established.

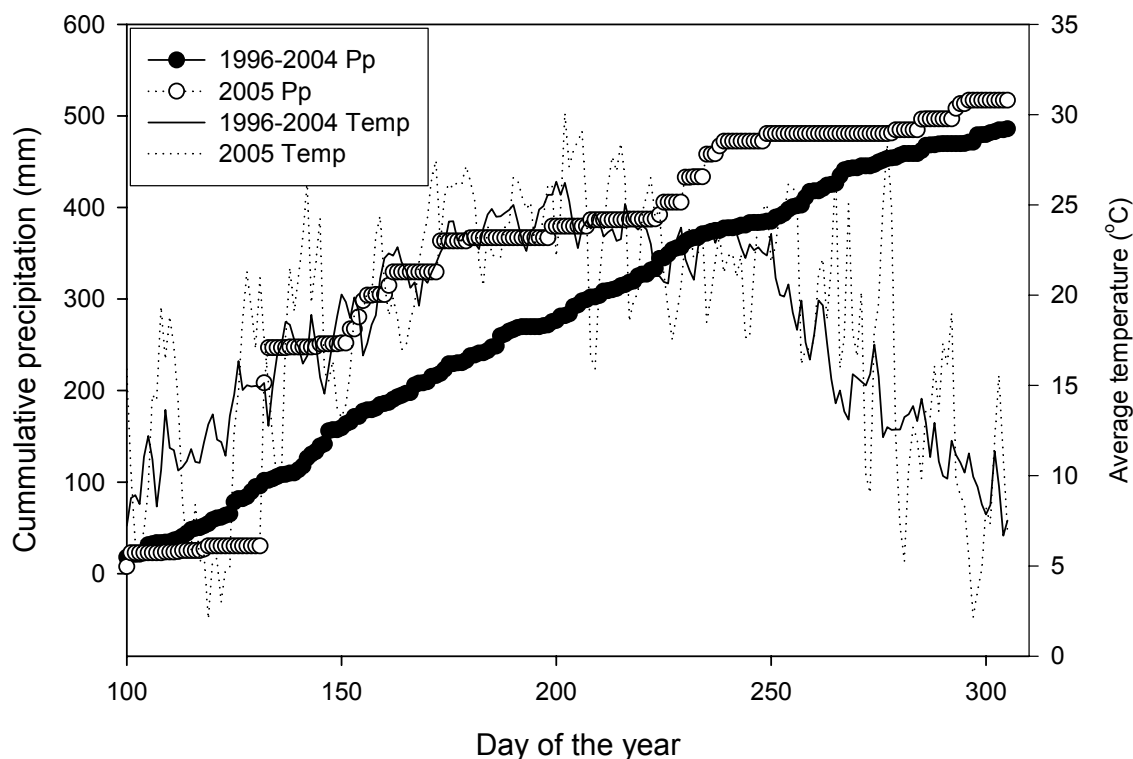


Figure 1: Long term and 2005 average temperatures and cumulative precipitation for the period April-October at the MSEA site, Shelton, NE

Nitrogen Effects on Vegetation Indices and Leaf Chlorophyll

Nitrogen was applied in varying amounts and at different growth stages at the three study sites in an attempt to create canopy variation in N status. The ANOVA for the three sites shown in Tables 1a, 2a, and 3a, demonstrates that N treatments affected SPAD-determined leaf chlorophyll measurements and sensor-determined vegetation indices (ANDVI, AR, WDRVI, and CHLI). However, these analyses indicated that leaf chlorophyll content and sensor readings were also affected by other factors including

hybrid, growth stage, and the interaction of N levels with these effects. Previous research with the chlorophyll meter (Schepers et al., 1992; Schepers, 1994) and sensors (Shanahan et al., 2003) also revealed that many variables besides N can potentially affect both leaf chlorophyll levels and vegetation indices, including hybrid, stage of growth, and environmental conditions. Since these readings can be affected by so many factors, it has been recommended (Schepers et al., 1992; Schepers, 1994; Peterson et al., 1993) that values should be normalized to an adequately fertilized N reference strip in each field and for each hybrid. Hence, we utilized a similar approach with the vegetation indices and chlorophyll data in this study. Vegetation indices and chlorophyll meter data were normalized, by converting absolute values to a percent of the average across N levels and replications within a given hybrid.

At all three sites, the effect of N on both relative SPAD (SI_{SPAD}) readings and sensor-determined VI's (SI_{SENSOR}) were apparent by the V11 growth stage (Tables 1b, 2b, and 3b), and continued throughout the remainder of vegetative growth period. For example at the SL and NK sites, there was a significant difference among N treatments for both SI_{SPAD} and SI_{SENSOR} during the reproductive growth stage period. However, at the NL site, N treatments had a significant effect on chlorophyll meter readings only, and not VIs, during reproductive growth. This contrasting response across the three sites is likely due to a combination of variation in stand establishment, residual soil N supply across the three sites, and presence of the tassel. The soil test result for residual N showed that the NL and NK sites were equally deficient in N, although plant distribution was different ($P < 0.0001$). A greater response to N for SPAD readings and VIs was expected throughout the entire growing season for the SL vs. the NL and NK sites since plots were

N depleted since 1991. However, in general, the N treatments used at our three study sites generated considerable variation in canopy N status across a range of growth stages, as determined by both chlorophyll meter and active sensor readings.

Table 1a: Significance levels from ANOVA for each vegetation index for the South Linear field.

GDD †	Effect	df	-----Pr>F-----				
			SPAD	ANDVI	AR	WDRVI	CHLI
500 (V9)	Hyb	1	*	NS	NS	NS	NS
	N_p	4	***	**	**	**	**
	HYB*N_p	4	#	NS	NS	NS	NS
600 (V11)	Hyb	1	#	NS	*	*	*
	N_p	4	**	*	*	*	*
	HYB*N_p	4	NS	NS	NS	NS	NS
700 (V15)	Hyb	1	**	*	*	*	*
	N_p	4	***	***	***	***	***
	HYB*N_p	4	*	**	***	***	***
800 (R1)	Hyb	1	**	**	**	**	**
	N_p	4	**	***	***	***	***
	HYB*N_p	4	#	NS	NS	NS	NS
1000 (R3)	Hyb	1	**	**	***	***	***
	N_p	4	***	***	***	***	***
	HYB*N_p	4	NS	NS	NS	NS	NS

N_p=N at planting, Hyb= hybrid

NS= non significant; # = significant at P<0.10

*Statistical significance at P<0.05

** Statistical significance at P<0.01

*** Statistical significance at P<0.001

Table 1b: Significance levels from ANOVA for each relative vegetation index for the South Linear field.

GDD †	Effect	df	-----Pr>F-----				
			SPAD	ANDVI	AR	WDRVI	CHLI
500 (V9)	Hyb	1	NS	NS	NS	NS	NS
	N_p	4	***	**	*	**	**
	HYB*N_p	4	#	NS	NS	NS	NS
600 (V11)	Hyb	1	NS	*	*	*	*
	N_p	4	***	*	*	*	*
	HYB*N_p	4	#	NS	NS	NS	NS
700 (V15)	Hyb	1	NS	NS	NS	NS	NS
	N_p	4	***	***	***	***	***
	HYB*N_p	4	**	**	**	***	**
800 (R1)	Hyb	1	**	NS	NS	NS	NS
	N_p	4	**	***	***	***	***
	HYB*N_p	4	NS	NS	NS	NS	NS
1000 (R3)	Hyb	1	NS	NS	NS	NS	NS
	N_p	4	***	***	***	***	***
	HYB*N_p	4	NS	NS	NS	NS	NS

N_p=N at planting, Hyb= hybrid

NS= non significant, # = significant at P<0.10

*Statistical significance at P<0.05

** Statistical significance at P<0.01

*** Statistical significance at P<0.001

Table 2a: Significance levels from ANOVA for each vegetation index for the North Linear field.

GDD †	Effect	df	SPAD	ANDVI	AR	WDRVI	CHLI
500 (V9)	Ftime	1	NS	NS	NS	NS	NS
	N_p	3	NS	**	**	**	**
	Ftime*N_p	3	NS	NS	NS	NS	NS
	IS	4	NS	NS	NS	NS	NS
	Ftime*IS	4	NS	NS	NS	NS	NS
	N-p*IS	8	NS	NS	NS	NS	NS
	Ftime*N_p*IS	8	NS	NS	NS	NS	NS
600 (V11)	Ftime	1	NS	NS	NS	NS	NS
	N_p	3	***	**	**	**	**
	Ftime*N_p	3	NS	NS	NS	NS	NS
	IS	4	#	NS	NS	NS	NS
	Ftime*IS	4	NS	NS	NS	NS	NS
	N-p*IS	8	NS	NS	NS	NS	NS
	Ftime*N_p*IS	8	NS	NS	NS	NS	NS
700 (V15)	Ftime	1	NS	NS	NS	NS	NS
	N_p	3	***	***	***	***	***
	Ftime*N_p	3	*	*	*	*	*
	IS	4	NS	NS	NS	NS	NS
	Ftime*IS	4	NS	NS	NS	NS	NS
	N-p*IS	8	NS	NS	NS	NS	NS
	Ftime*N_p*IS	8	NS	NS	NS	NS	NS
800 (R1)	Ftime	1	NS	NS	NS	NS	NS
	N_p	3	***	**	**	**	**
	Ftime*N_p	3	*	NS	NS	NS	NS
	IS	4	NS	NS	NS	NS	NS
	Ftime*IS	4	*	NS	NS	NS	NS
	N-p*IS	8	NS	NS	NS	NS	NS
	Ftime*N_p*IS	8	NS	NS	NS	NS	NS
900 (R2)	Ftime	1	#	NS	NS	NS	NS
	N_p	3	***	NS	#	#	#
	Ftime*N_p	3	#	NS	NS	NS	NS
	IS	4	**	NS	NS	NS	NS
	Ftime*IS	4	NS	NS	NS	NS	NS
	N-p*IS	8	#	NS	NS	NS	NS
	Ftime*N_p*IS	8	#	NS	#	NS	#
1000 (R3)	Ftime	1	NS	NS	NS	NS	NS
	N_p	3	#	NS	NS	NS	NS
	Ftime*N_p	3	NS	NS	NS	NS	NS
	IS	4	NS	*	*	*	*
	Ftime*IS	4	NS	NS	NS	NS	NS
	N-p*IS	8	NS	NS	NS	NS	NS
	Ftime*N_p*IS	8	NS	NS	NS	NS	NS

N_p=N at planting, Ftime=Fertilization date, IS=in season fertilization

NS= non significant, # = significant at P<0.10

*Statistical significance at P<0.05

** Statistical significance at P<0.01

*** Statistical significance at P<0.001

Table 2b: Significance levels from ANOVA for each relative vegetation index for the North Linear field.

GDD †	Effect	df	SPAD	ANDVI	AR	-----Pr>F-----	
						WDRVI	CHLI
500 (V9)	Ftime	1	NS	***	**	NS	**
	N_p	3	***	***	**	**	***
	Ftime*N_p	3	NS	NS	NS	NS	NS
	IS	4	#	NS	NS	NS	NS
	Ftime*IS	4	NS	NS	NS	NS	NS
	N-p*IS	8	NS	NS	NS	NS	NS
	Ftime*N_p*IS	8	NS	NS	NS	NS	NS
600 (V11)	Ftime	1	NS	#	#	#	#
	N_p	3	***	**	**	**	**
	Ftime*N_p	3	#	NS	NS	NS	NS
	IS	4	NS	NS	NS	NS	NS
	Ftime*IS	4	NS	NS	NS	NS	NS
	N-p*IS	8	NS	NS	NS	NS	NS
	Ftime*N_p*IS	8	NS	NS	NS	NS	NS
700 (V15)	Ftime	1	NS	NS	NS	NS	NS
	N_p	3	***	***	***	***	***
	Ftime*N_p	3	*	*	*	*	*
	IS	4	NS	NS	NS	NS	NS
	Ftime*IS	4	*	NS	NS	NS	NS
	N-p*IS	8	NS	NS	NS	NS	NS
	Ftime*N_p*IS	8	NS	NS	NS	NS	NS
800 (R1)	Ftime	1	NS	NS	NS	NS	NS
	N_p	3	***	**	**	**	**
	Ftime*N_p	3	*	NS	NS	NS	NS
	IS	4	*	NS	NS	NS	NS
	Ftime*IS	4	NS	NS	NS	NS	NS
	N-p*IS	8	#	NS	NS	NS	NS
	Ftime*N_p*IS	8	#	NS	NS	NS	NS
900 (R2)	Ftime	1	NS	NS	NS	NS	NS
	N_p	3	***	NS	#	#	#
	Ftime*N_p	3	#	NS	NS	NS	NS
	IS	4	NS	NS	NS	NS	NS
	Ftime*IS	4	NS	NS	NS	NS	NS
	N-p*IS	8	NS	NS	NS	NS	NS
	Ftime*N_p*IS	8	NS	NS	NS	#	NS
1000 (R3)	Ftime	1	NS	NS	NS	NS	NS
	N_p	3	***	NS	NS	NS	NS
	Ftime*N_p	3	#	NS	NS	NS	NS
	IS	4	**	*	*	*	*
	Ftime*IS	4	NS	NS	NS	NS	NS
	N-p*IS	8	NS	NS	NS	NS	NS
	Ftime*N_p*IS	8	NS	NS	NS	NS	NS

N_p=N at planting, Ftime=Fertilization date, IS=in season fertilization

NS= non significant, # = significant at P<0.10

*Statistical significance at P<0.05

** Statistical significance at P<0.01

*** Statistical significance at P<0.001

Table 3a: Significance levels from ANOVA for each vegetation index for the Niemack field.

GDD †	Effect	df	SPAD	ANDVI	AR	WDRVI	CHLI
600 (V11)	Ftime	1	NS	NS	NS	NS	NS
	N_p	3	***	***	***	***	***
	Ftime*N_p	3	NS	#	NS	NS	NS
	IS	4	NS	*	*	*	*
	Ftime*IS	4	NS	NS	NS	NS	NS
	N-p*IS	8	NS	NS	NS	NS	NS
	Ftime*N_p*IS	8	NS	NS	NS	NS	NS
700 (V15)	Ftime	1	NS	NS	NS	NS	NS
	N_p	3	***	***	***	***	***
	Ftime*N_p	3	NS	NS	#	#	#
	IS	4	NS	**	**	**	**
	Ftime*IS	4	NS	NS	NS	NS	NS
	N-p*IS	8	NS	#	#	*	#
	Ftime*N_p*IS	8	NS	**	*	*	*
900 (R2)	Ftime	1	NS	NS	NS	NS	NS
	N_p	3	***	**	**	**	**
	Ftime*N_p	3	NS	NS	NS	NS	NS
	IS	4	***	***	***	***	***
	Ftime*IS	4	NS	NS	NS	NS	NS
	N-p*IS	8	*	**	**	**	**
	Ftime*N_p*IS	8	*	NS	#	NS	#
1000 (R4)	Ftime	1	NS	NS	NS	NS	NS
	N_p	3	***	*	**	**	**
	Ftime*N_p	3	NS	NS	#	#	#
	IS	4	***	***	***	***	***
	Ftime*IS	4	NS	NS	NS	NS	NS
	N-p*IS	8	NS	NS	NS	NS	NS
	Ftime*N_p*IS	8	NS	*	*	*	*

N_p=N at planting, Ftime=Fertilization date, IS=in season fertilization

NS= non significant, # = significant at P<0.10

*Statistical significance at P<0.05

** Statistical significance at P<0.01

*** Statistical significance at P<0.001

Table 3b: Significance levels from ANOVA for each relative vegetation index for the Niemack field.

GDD †	Effect	df	SPAD	ANDVI	AR	WDRVI	CHLI
600 (V11)	Ftime	1	NS	NS	NS	NS	NS
	N_p	3	***	***	***	***	***
	Ftime*N_p	3	NS	#	NS	NS	NS
	IS	4	NS	*	*	*	*
	Ftime*IS	4	NS	NS	NS	NS	NS
	N-p*IS	8	NS	NS	NS	NS	NS
	Ftime*N_p*IS	8	NS	NS	NS	NS	NS
700 (V15)	Ftime	1	NS	NS	NS	NS	NS
	N_p	3	***	***	***	***	***
	Ftime*N_p	3	NS	NS	#	#	#
	IS	4	NS	**	**	**	**
	Ftime*IS	4	NS	#	NS	NS	NS
	N-p*IS	8	#	*	#	#	#
	Ftime*N_p*IS	8	NS	**	*	*	*
900 (R2)	Ftime	1	NS	NS	NS	NS	NS
	N_p	3	***	**	**	**	**
	Ftime*N_p	3	NS	NS	NS	NS	NS
	IS	4	***	***	***	***	***
	Ftime*IS	4	#	NS	NS	NS	NS
	N-p*IS	8	*	**	**	**	**
	Ftime*N_p*IS	8	*	NS	NS	NS	NS
1000 (R4)	Ftime	1	**	NS	NS	NS	NS
	N_p	3	***	*	**	**	*
	Ftime*N_p	3	NS	NS	NS	NS	NS
	IS	4	***	***	***	***	***
	Ftime*IS	4	NS	NS	NS	NS	NS
	N-p*IS	8	NS	NS	NS	NS	NS
	Ftime*N_p*IS	8	NS	NS	NS	NS	NS

N_p=N at planting, Ftime=Fertilization date, IS=in season fertilization

NS= non significant, # = significant at P<0.10

*Statistical significance at P<0.05

** Statistical significance at P<0.01

*** Statistical significance at P<0.001

Association between Leaf Chlorophyll and Vegetation Indices

Subsequent to confirming that our N treatments produced variability in canopy greenness, we were also interested in determining if there was an association between SPAD-determined assessments of canopy greenness and independently determined sensor estimates of canopy greenness. To accomplish this task we used linear regression analysis to examine relationships between variation in relative chlorophyll meter readings and variation in the four vegetation indices, testing for the presence of both linear and quadratic components in each relationship. Both the coefficient of determination (R^2) and the F test for regression (P value for regression of < 0.05) were used as criterion establishing a significant association. Using these criteria, only one quadratic relationship was detected that involved a growth stage for a single hybrid planted at the SL site. Therefore, only the linear aspects of these relations are presented and discussed (Table 4). Significant linear associations between relative SPAD readings and values for the four vegetation indices were observed for many of the vegetative growth stages and study sites in 2005. The relationships were positive for the leaf chlorophyll vs. RANDVI, RAR, and RCHLI values and negative for RSPAD vs. RWDRVI readings (Table 4). The negative association between SPAD and RWDRVI was expected considering the low alpha value used (0.1). During reproductive growth, fewer significant relationships between leaf chlorophyll readings and the four vegetation indices were observed.

Table 4: Linear regression between different relative vegetation indices and relative SPAD values.

GDD	-----ANDVI-----			-----AR-----			-----WDRVI-----			-----CHLI-----		
	R2	Slope	RMSE	R2	Slope	RMSE	R2	Slope	RMSE	R2	Slope	RMSE
South Linear P31N27												
500 (V9)	0.307*	0.508	0.04	0.275*	0.9167	0.078	0.29*	-1.257	0.079	0.273*	1.159	0.099
600 (V11)	0.468**	0.275	0.031	0.506**	0.612	0.065	0.578***	-1.107	0.102	0.495**	0.751	0.082
700 (V15)	0.524**	0.561	0.04	0.549**	1.086	0.075	0.592***	-2.055	0.131	0.546**	1.326	0.092
800 (R1)	0.784***	0.245	0.013	0.812***	0.652	0.033	0.80***	-0.470	0.09	0.812***	0.775	0.04
1000 (R3)	0.33**	0.232	0.041	0.660***	0.513	0.046	0.124NS	-0.623	0.206	0.663***	0.638	0.056
South Linear P33V15												
500 (V9)	0.427**	0.452	0.036	0.436**	0.884	0.069	0.421**	-1.141	0.092	0.434**	1.128	0.089
600 (V11)	0.044NS	0.136	0.048	0.047NS	0.288	0.099	0.049NS	-0.269	0.091	0.046NS	0.388	0.135
700 (V15)	0.81***	0.685	0.033	0.77**	1.397	0.073	0.77**	-3.004	0.158	0.77**	1.681	0.088
800 (R1)	0.118NS	0.125	0.0043	0.115NS	0.266	0.092	0.111#	-0.171	0.179	0.117NS	0.325	0.112
1000 (R3)	0.294*	0.192	0.036	0.481**	0.411	0.052	0.052NS	-0.208	0.108	0.480**	0.531	0.067
North Linear												
500 (V9)	0.006NS	-0.054	0.069	0.000NS	0.002	0.109	0.001NS	-0.017	0.048	0.0001NS	-0.012	0.146
600 (V11)	0.339***	0.705	0.060	0.336***	1.241	0.106	0.327***	-0.607	0.053	0.339***	1.612	0.137
700 (V15)	0.364***	0.503	0.039	0.389***	1.077	0.080	0.405***	-0.689	0.049	0.389***	1.322	0.098
800 (R1)	0.467***	0.03	0.028	0.485***	0.661	0.059	0.419***	-0.426	0.044	0.485***	0.814	0.073
900 (R2)	0.004NS	0.015	0.015	0.016NS	0.056	0.030	0.013NS	-0.023	0.014	0.016NS	0.072	0.039
1000 (R3)	0.030*	-0.552	0.020	0.024#	-0.090	0.037	0.025#	0.041	0.017	0.024#	-0.117	0.048
Niemack												
600 (V11)	0.725***	0.661	0.035	0.774***	1.348	0.063	0.747***	-0.960	0.048	0.776***	1.618	0.075
700 (V15)	0.821***	0.453	0.021	0.848***	1.033	0.043	0.847***	-0.791	0.033	0.847***	1.227	0.051
900 (R2)	0.201***	-0.181	0.026	0.187***	-0.365	0.055	0.196***	0.156	0.023	0.185***	-0.481	0.073
1000 (R4)	0.042*	-0.126	0.037	0.04*	-0.233	0.075	0.042*	0.106	0.031	0.040*	-0.336	0.100

† RMSE, Root mean square error

NS: non significant; #, *, **, *** significant at P<0.1, P<0.05, P<0.01, and P<0.001 respectively

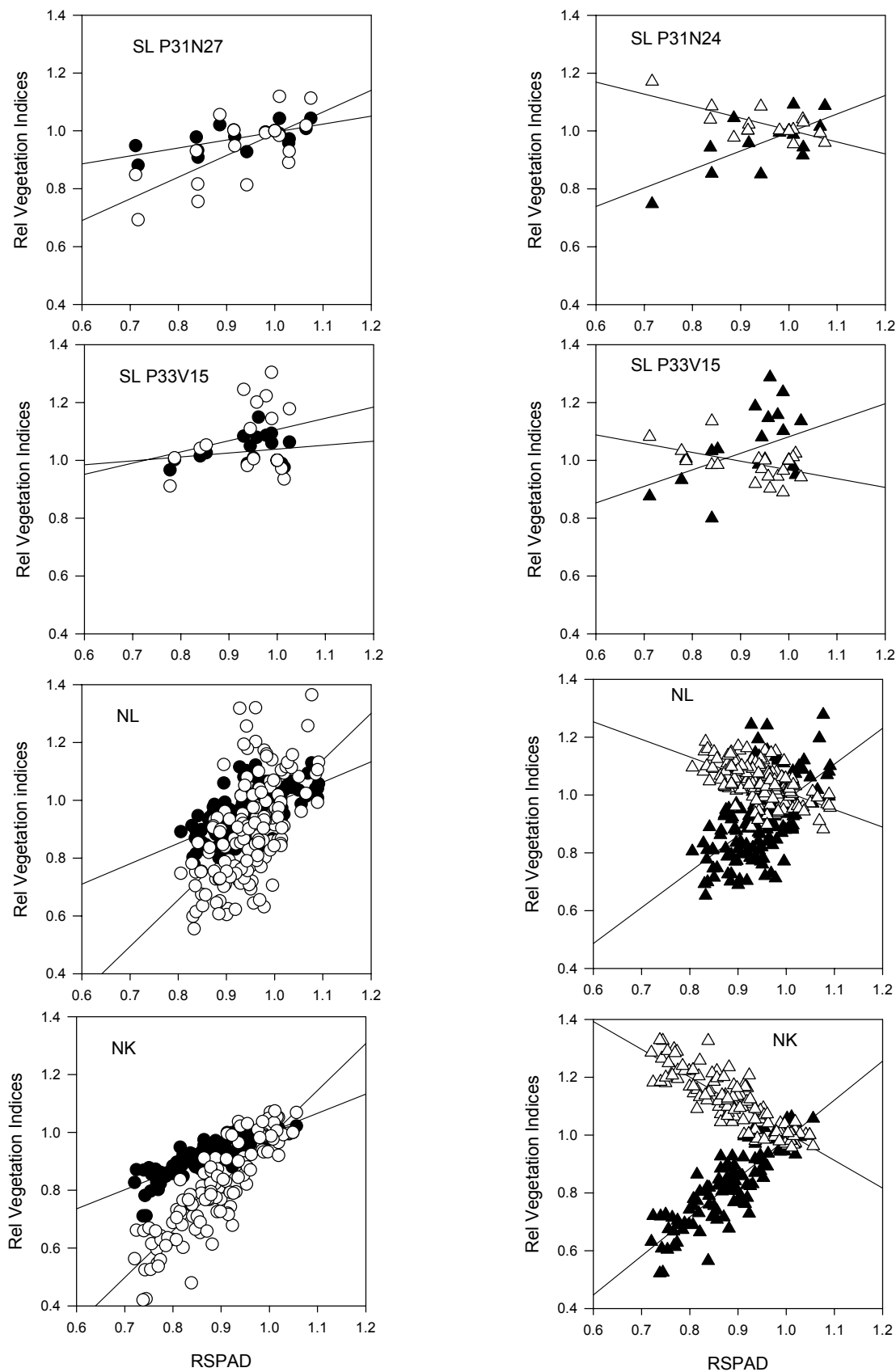


Figure 2a: Relations between RSPAD and relative vegetation indices at 600GDD (V11). RANDVI (closed circles), RCHLI (open circles), RWDRVI (open triangles), and RAR (closed triangles).

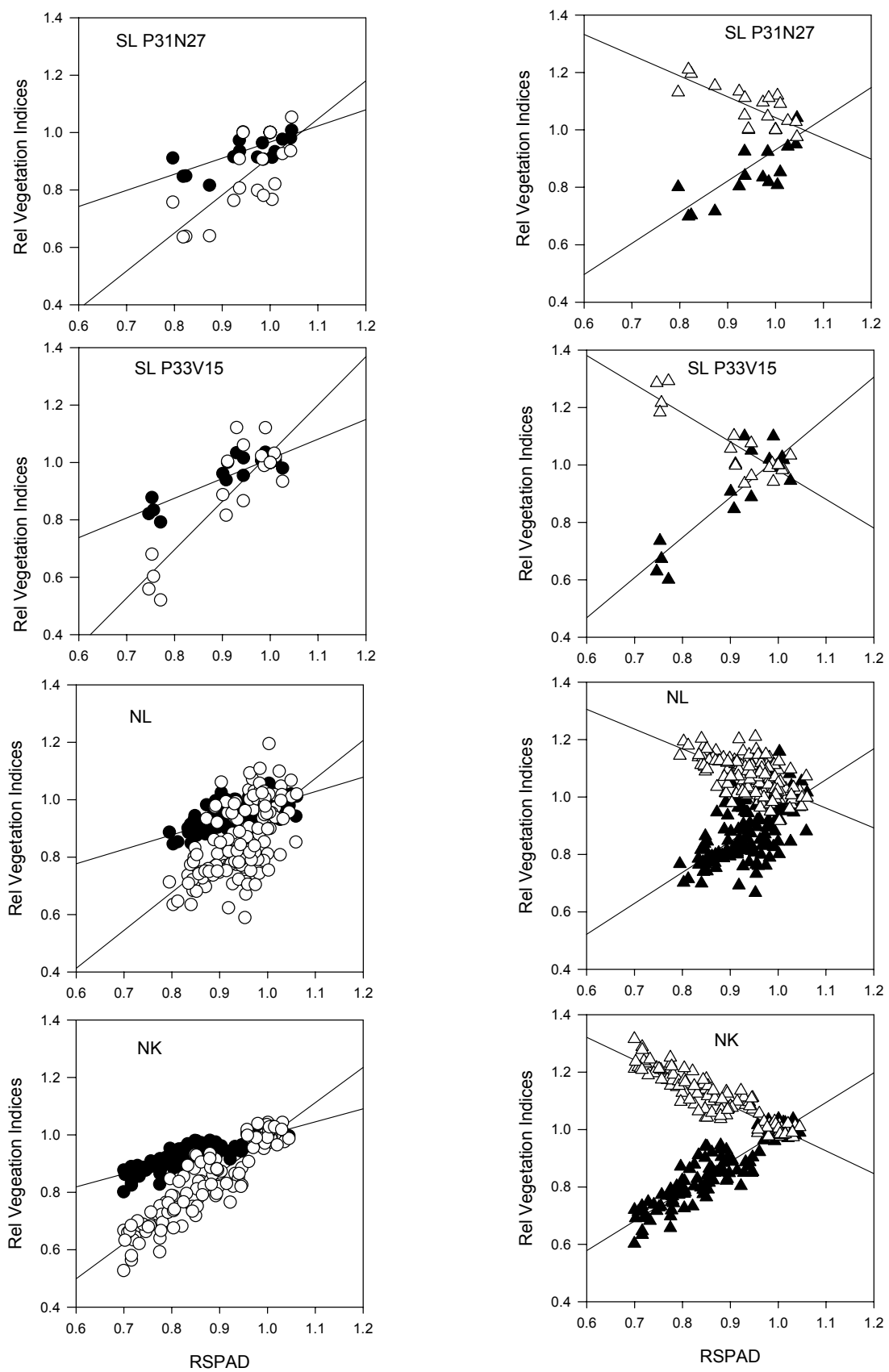


Figure 2b: Relation between RSPAD and relative vegetation indices at 700GDD (V15). RANDVI (closed circles), RCHLI (open circles), RWDRVI open triangles, and RAR (closed triangles).

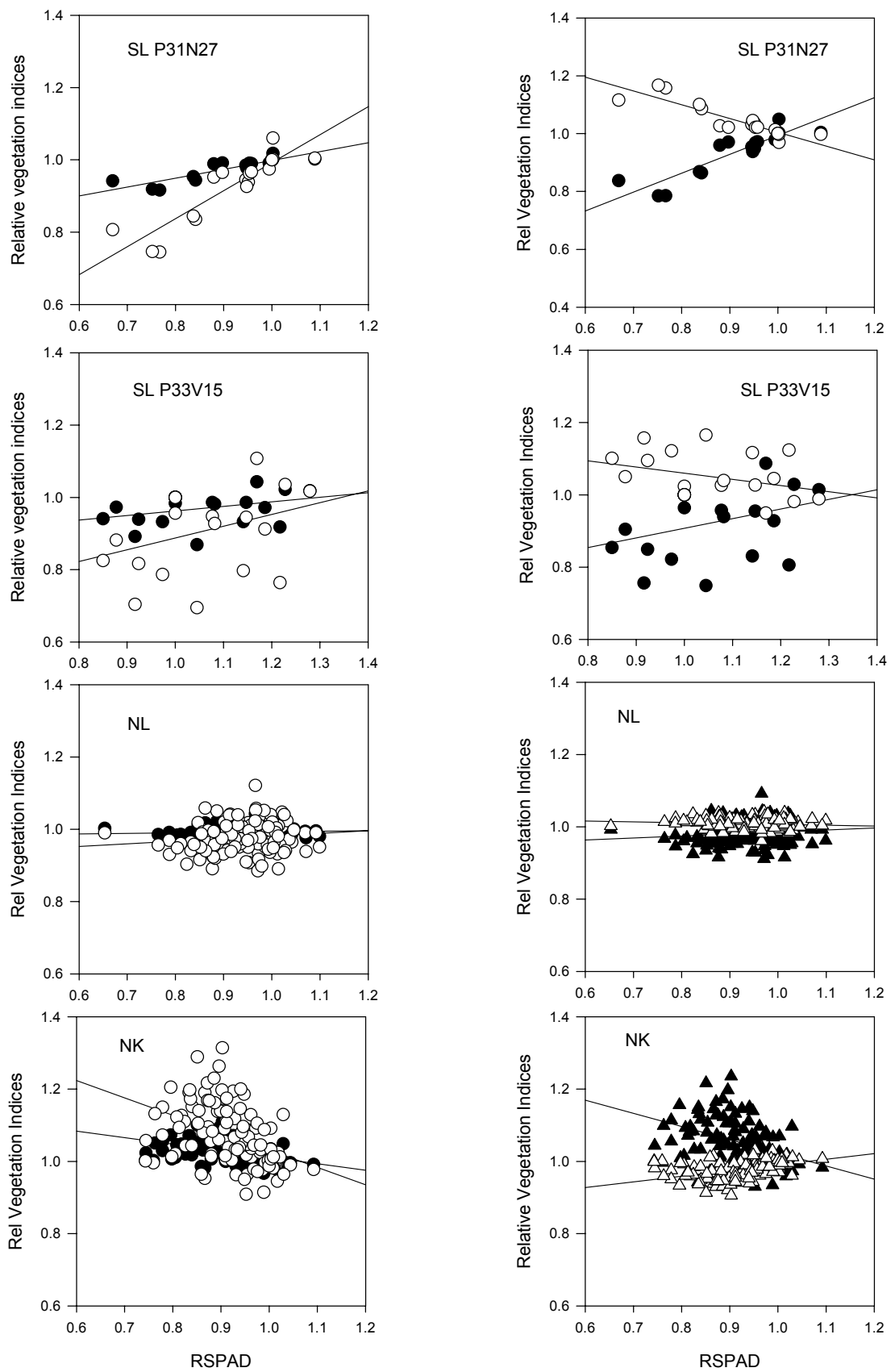


Figure 2c: Relation between RSPAD and relative vegetation indices at 900GDD (R1-2). RANDVI (closed circles), RCHLI (open circles), RWDRVI open triangles, and RAR (closed triangles).

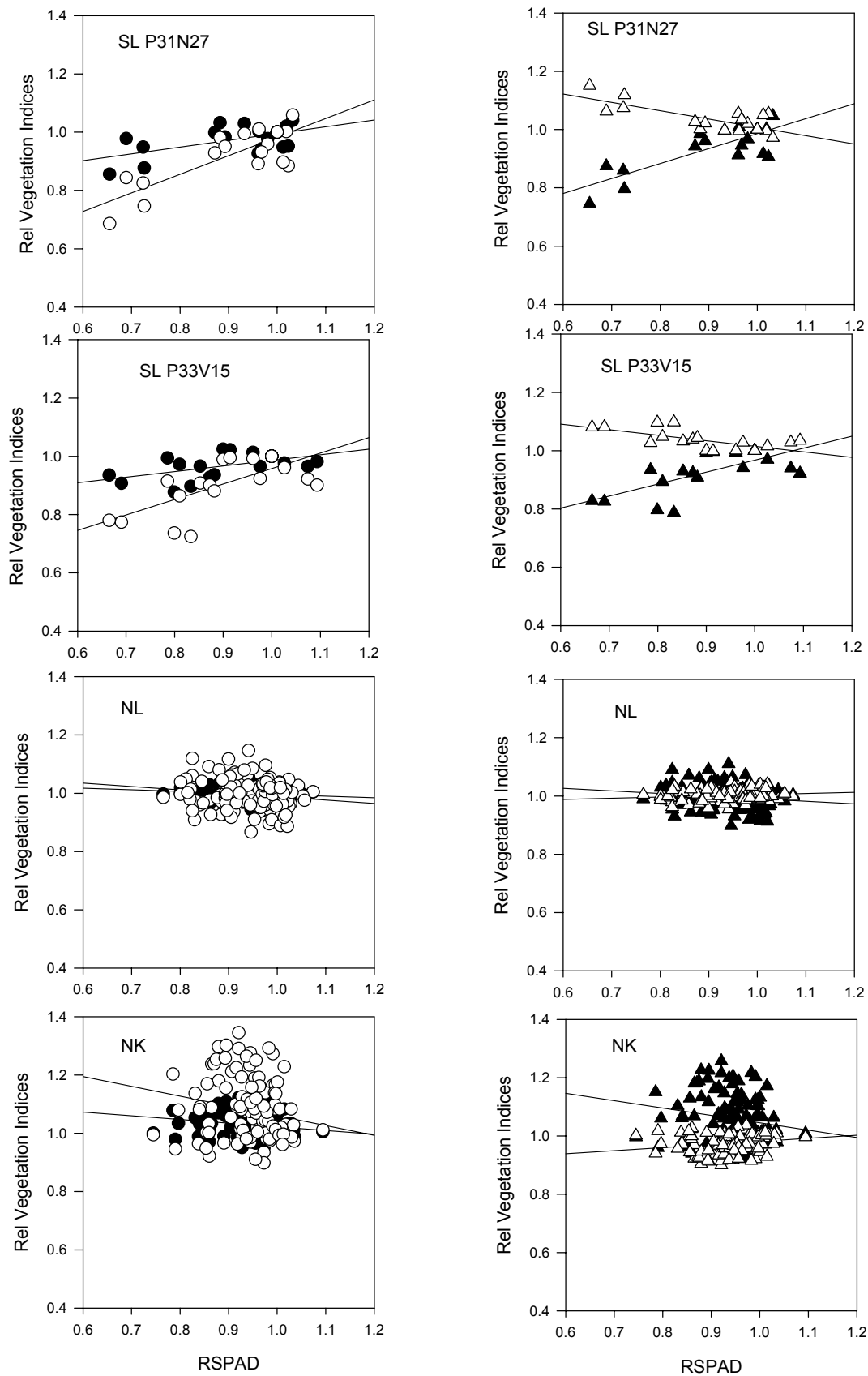


Figure 2d: Relation between RSPAD and relative vegetation indices at 1000GDD (R3-4). RANDVI (closed circles), RCHLI (open circles), RWDRVI open triangles, and RAR (closed triangles).

The difference in the degree of association between sensor and chlorophyll meter readings across growth stages and fields was not surprising, given that chlorophyll meter readings were collected from individual leaves while the sensor's field of view allowed us to measure more of the plant canopy, consisting of intermingled leaves of different plants. Color and N differences are known to exist along the leaf blade (Piekielek and Fox, 1992; Chapman and Barreto, 1997; Drouet and Bonhomme, 1999) and vertically along the plant (Plénet, 1995; Drouet and Bonhomme, 1999). Sensor readings integrate the whole canopy while SPAD reading represent point measurements. Early in the season plant population and/or an uneven plant distribution will affect the variability in sensor readings because of different proportions of soil and leaves are sensed in the field of view. The intense rainfall episode soon after planting and before emergence affected plant distribution at the NL site compared to the NK site ($P < 0.0001$) that was already emerged at that time. This can be a reason for a consistently lower R^2 value for the linear regressions in the NL and SL fields than in the NK field (Table 4). As the season progresses and canopy grows, some void areas are filled and the variability in sensor readings decreases. In the same way, and especially for the field with a more uniform stand, the plots with higher N availability grew faster and consequently had the lowest CV values at V16 (Figure 3).

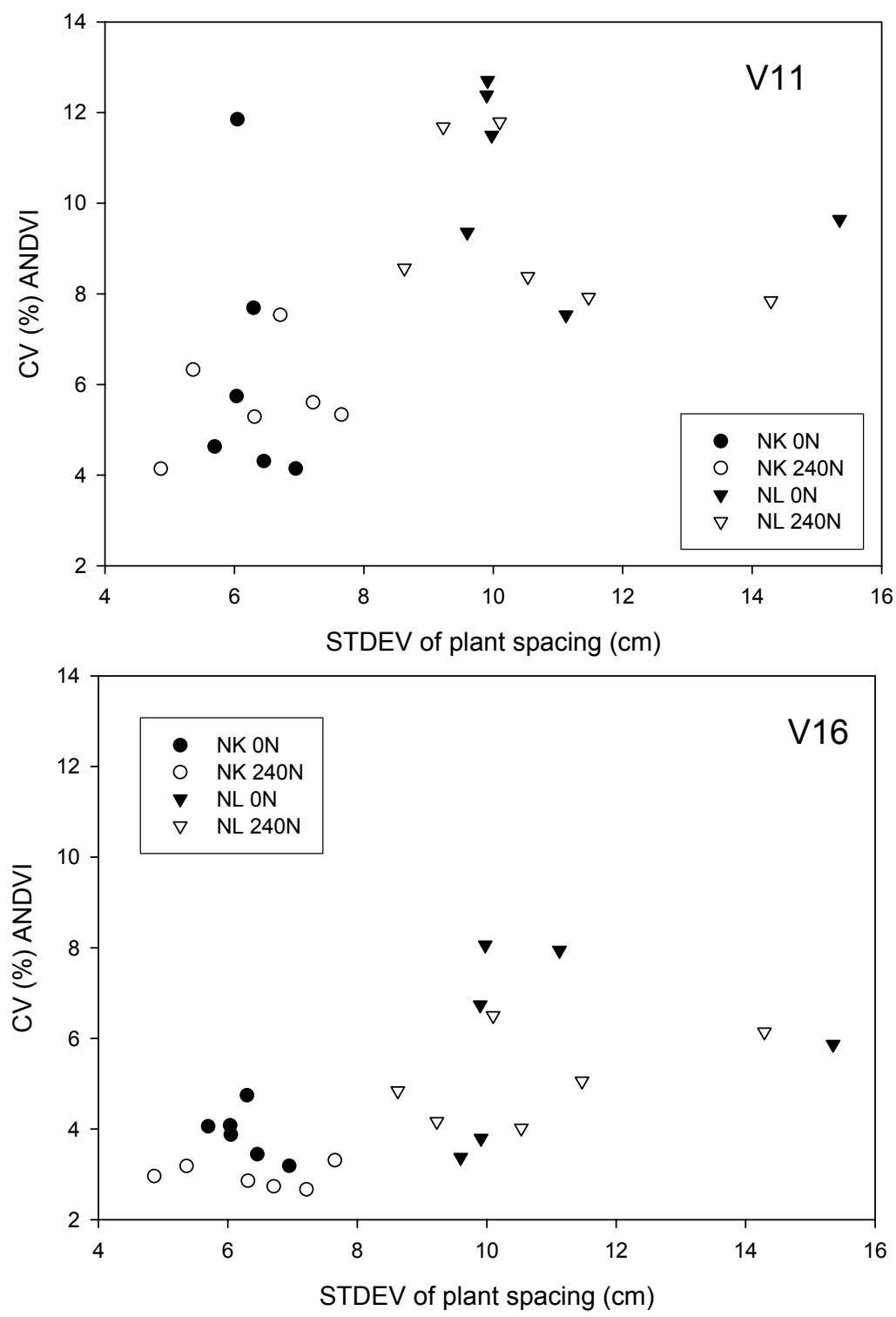


Figure 3: CV (%) values of ANDVI within plots at the V11 and V15 growth stages

Selection of a vegetation index for estimation of relative Chl content

To address our study objective of establishing which growth stage and vegetation index is most sensitive for remotely sensing variation in corn canopy N status, we further explored the linear associations between SPAD readings and the sensor-determined VI, evaluating the slope, R², and RMSE statistics as criteria for determining which growth stage and VI was most sensitive. The SPAD readings increased throughout the season for a given N treatment in all fields. Conversely, ANDVI, Chl index, Amber ratio and WDRVI increased in absolute terms during vegetative stages and then decreased during reproductive stages. These vegetation indices are combinations of reflectance in the NIR and amber portions of the spectrum. Figure 5 shows the evolution of amber and NIR reflectance for the 0, 160 and 240 kg N ha⁻¹ treatments in the NK field throughout the season. The shape of the curve is similar for the three fields. During vegetative growth stages, amber reflectance decreased as canopy grew in all treatments and hybrids because Chl content increases and less soil is in the field of view. The corn tassel has no chlorophyll pigment, is closer to the sensor, and has a larger influence on the readings than leaves further from the sensor. Therefore, when tassels emerged, amber reflectance peaked. Around R2, the tassel is still vigorous and occupies a significant portion of the sensor's field of view. Later in the season, the tassel loses biomass and fills a smaller proportion of the sensor's field of view and blocks less light. Consequently, the light emitted by the sensor reaches lower canopy layers and is absorbed by leaves with chlorophyll. Therefore, amber reflectance decreases again. As a result the linear relationship between SPAD readings and vegetation indices found during vegetative stages cannot be maintained after tassel emergence (Figure 2c and d).

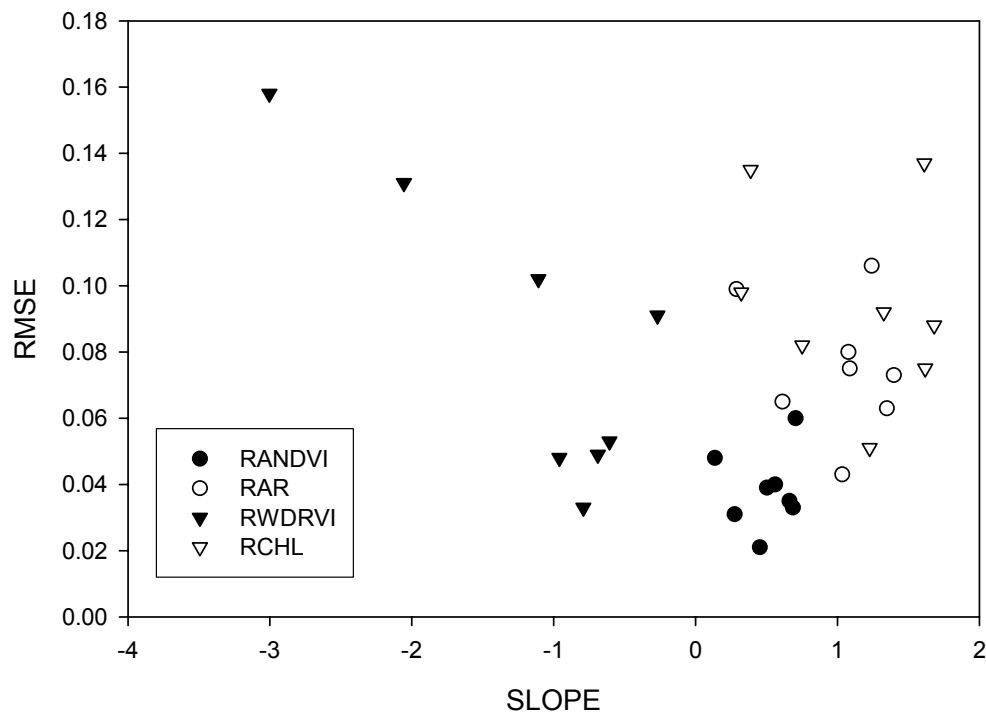


Figure 4: Relationship between slope and RMSE for the four indices during vegetative growth stages.

Vegetation indices that include a NIR term are intended to consider a biomass component. For example, in the Chl index

$$\text{Chl index} = (1/\text{Amber} - 1/\text{NIR}) * \text{NIR} \quad \text{or} \quad (\text{NIR}/\text{Amber}) - 1$$

The $(1/\text{Amber})$ term is intended to be maximally sensitive to Chl absorption. However, because amber reflectance is also affected by the absorption of other constituents and backscattering, a second term with a spectral region (NIR) such that $(1/\text{NIR})$ is minimally sensitive to the pigment of interest, and for which the absorption by other constituents is almost equal to that at Amber is subtracted. A third term (NIR) minimally affected by the absorption of pigments is used to compensate for the variability in backscattering due to leaf thickness and canopy architecture.

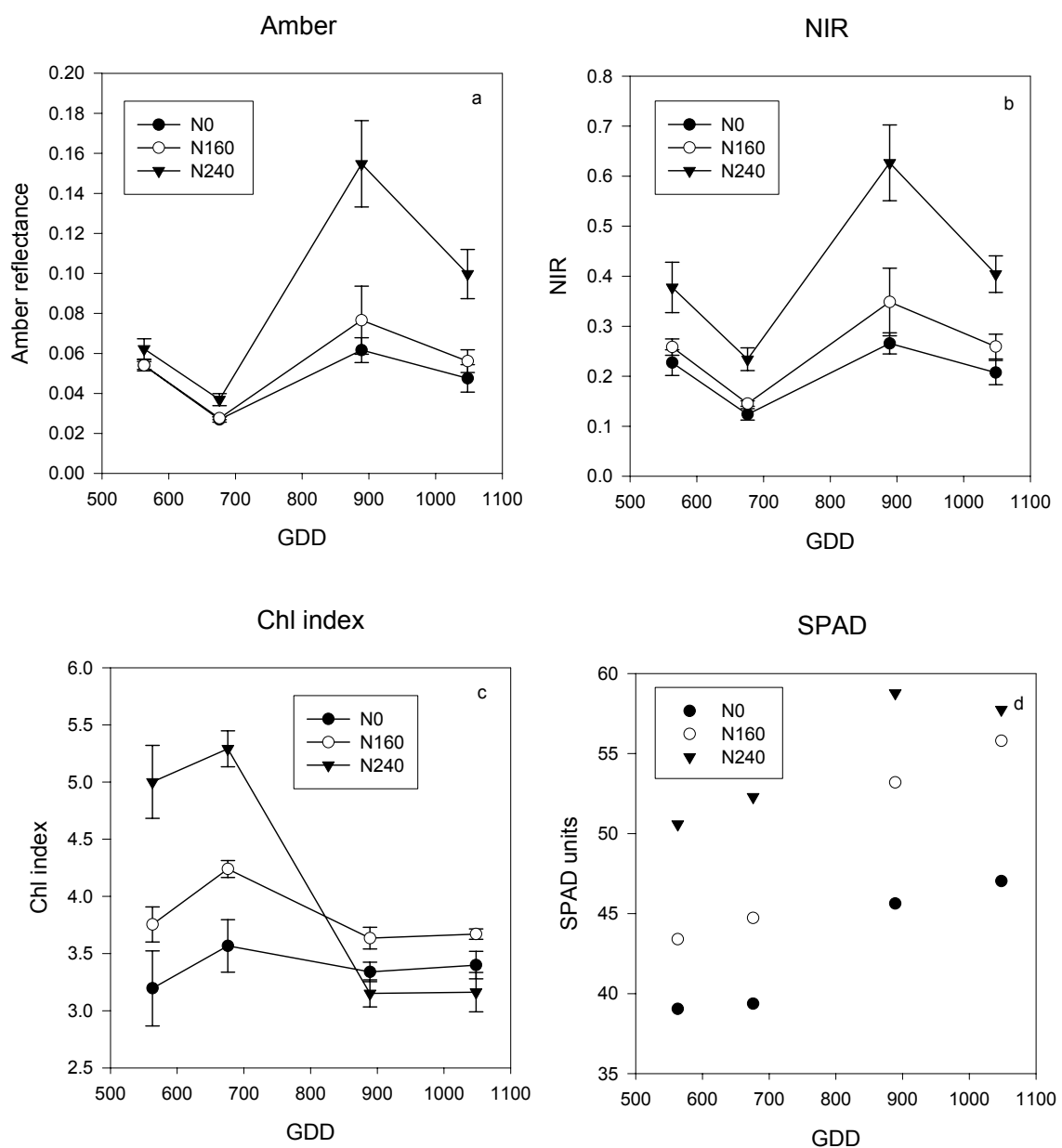


Figure 5: Evolution of amber reflectance (a), NIR reflectance (b), Chl index (c), and SPAD units (d), NK site.

In addition to the presence of the tassel, some active sensors' characteristics affecting NIR reflectance may contribute to this lack of fit. The energy of light decreases

as distance between the sensor and the target increases following the inverse square law. Because of its low energy source of light ($<10\mu\text{Wm}^{-2}$ to 1mWm^{-2}) the NIR band from this active sensor can only penetrate 5-6 layers of leaves. As such, light emitted from the active sensor seldom reaches the ear leaf with the NIR band when placed 1.0 m above the canopy (data shown in Chapter 1). The amber band is absorbed in the uppermost layer of leaves that is not always representative of the total amount of Chl of the crop. The vertical distribution of N in a crop canopy is not uniform (Plénet, 1995 (maize); Anten et al., 1995 (sorghum); Connor et al., 1995 (sunflower); Grindlay, 1997 (several crops); Dreccer et al., 2000 (wheat)), especially during reproductive stages. In a corn canopy for example, the majority of leaf area is located in the central portion of the plant around the ear leaf (Boedhram et al., 2001), and so is the largest amount of Chl content (Osaki et al., 1995a, 1995b) and N (Drouet and Bonhomme, 1999). Therefore, not reaching the main portion of the canopy with NIR radiation can impair the ability to correctly estimate the relative Chl status of the crop after tasseling. In terms of N fertilizer applications this may be immaterial, as most of our efforts are centered in the period between V9 to pre silking.

The four VIs tested here were linearly related with relative SPAD units in the range explored, and can be used to estimate relative Chl status. Our results indicate that RCHLI, RAR, and RWDRVI were more sensitive than RANDVI to variations in RSPAD values. However RANDVI showed the lowest RMSE values (Table 4 and Figure 2a). RANDVI sensitivity to variations in RSPAD decreases as season progress (Figure 2a, b, c, and d). Red NDVI has the limitation that it saturates asymptotically under conditions of moderate-to-high aboveground biomass with $\text{LAI} > 2$ (Gitelson, 1996; Miyneni et al., 1997). Previous work has shown an association between NDVI values and crop biomass

accumulation, leaf area index, leaf chlorophyll levels, and photosynthetically active radiation absorbed by the canopy (Tucker, 1979; Sellers, 1985; Sellers, 1987), which has in turn been associated with crop yield (Wiegand et al., 1994, Aparicio et al., 2000). However, when chlorophyll content, vegetation fraction, and leaf area index reach moderate to high values, NDVI is apparently less sensitive to these biophysical parameters. Thus, Gitelson et al. (1996) have proposed that the green band (GNDVI) is more sensitive than the red band (NDVI or TSAVI) in detecting leaf chlorophyll variation. While reflectance in the visible region exhibits a nearly flat response once the LAI exceeds 2, NIR reflectance continues to respond significantly to changes in moderate-to-high vegetation density (LAI from 2 to 6) in crops. However, this higher sensitivity of the NIR reflectance has little effect on NDVI values once the NIR reflectance exceeds 30% (Gitelson, 2004), a value reached at V11 in all sites (Ocean Optics data, not shown). The sensitivity of RWDRVI was 1.5 to 1.75 times greater than that of RANDVI in the NK study and up to 5 times greater in the SL study with the planophile hybrid. As expected, with an irregular plant distribution (NL study) the sensitivity of RWDRVI and RANDVI were similar (Table 3). These results agree with those of Gitelson (2004) where the sensitivity of the WDRVI to moderate-to-high LAI (between 2 and 6) was at least three times greater than that of ANDVI. Two recent studies also demonstrate how WDRVI increases sensitivity in moderate to high vegetation stands when compared with NDVI (Viña et al., 2004, Viña and Gitelson, 2005).

From a practical point of view, what we want is not only the most sensitive (slope closer to 1) and accurate (lower RMSE) index, but also an index that can be used across

growth stages for in-season fertilization. The slopes of the relationship between RSPAD and RAR, and RSPAD with RCHLI index were different for V11 and V15 and also between some fields. Conversely the relationships for RANDVI and RWDRVI were insensitive to growth stage during the vegetative period (Table 5). A common regression line was fitted between RWDRVI and RSPAD (Figure 6) because the slopes did not differ between fields (table 5). The model explained 60% of the variation in RSPAD readings with RMSE = 0.05. In general, the points further from the regression line correspond to V11 measurements or plots with sparse or irregular distribution of plants (NL field). This reaffirms the need of obtaining a uniform spatial distribution of plants if we want to use active sensors to estimate the Chl status of a corn crop. The Chl index is indicative of total Chl in the canopy (Gitelson et al., 2005). Relative Chl index was the most sensitive to environmental conditions and separates not only vegetative from reproductive stages but also between vegetative stages and among fields (Tables 4 and 5). So the most appropriate model varied between field and growth stage combinations (Figure 2a, and b).

Table 5: Significance values for one degree of freedom comparison between slopes of linear models between RSPAD and RVI.

	RANDVI	RRATIO	RWDRVI	RChl index
Slope compared	-----Pr>F-----			
Veg vs. Rep	<0.0001	<0.0001	<0.0001	<0.0001
V11 vs. V15	0.591	0.035	0.865	<0.0001
R2 vs. R4	0.390	0.031	<0.0001	<0.0001
SL1 vs. SL3	0.999	0.268	0.826	<0.0001
SL1 vs. NL	0.001	0.246	0.704	<0.0001
SL1 vs. NK	0.0005	0.518	0.658	<0.0001
SL3 vs. NL	0.004	0.696	0.958	0.024
SL3 vs. NK	0.0026	0.048	0.920	<0.0001
NL vs. NK	0.760	<0.0001	0.897	<0.0001

Veg: Vegetative stages, Rep: reproductive stages, V11, V16, R2, R4: growing stages (Ritchie et al., 1992), SL1: South Linear Hybrid P31N27, SL3: South Linear Hybrid P33V15, NL: North Linear, NK: Niemack

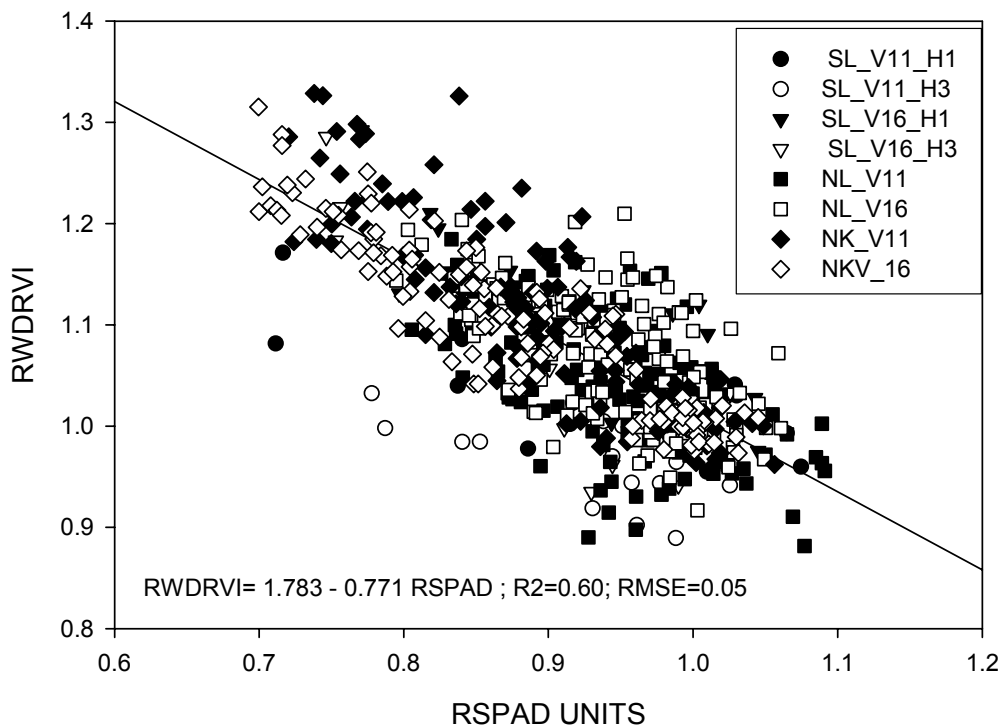


Figure 6: Linear relation between RWDRVI and RSPAD units during vegetative growth stages.

SUMMARY AND CONCLUSIONS

Over-application of N on corn has resulted in elevated levels of N in ground and surface waters. Our long term research objective is to reduce these over applications by developing technologies for in-season N application that use remote sensing of crop N status as a means to apply fertilizer when and where the crop can most efficiently use the N. Our results indicate that the sensor we evaluated provides information not only about relative Chl content but also about plant distribution and biomass. The four indices evaluated were linearly related with chlorophyll meter readings. RWDRVI, RCHLI, and RAR showed more sensitivity than RANDVI to variations in relative Chl content. Results from this work suggest that the active sensor system we evaluated is capable of detecting

variations in corn leaf chlorophyll status induced by varying levels of N application. More research is needed in order to validate these results in a wider range of climatic conditions and develop an algorithm for translating sensor reading into N fertilizer applications rates.

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Chapter 3

A framework for on-the-go nitrogen management in cornfields using active canopy sensors

ABSTRACT

A major factor contributing to decreased N use efficiency and environmental contamination for traditional corn N management schemes is routine pre-season application of large doses of N before the crop can effectively utilize this N. A major constraint to variable rate in-season N application for corn is having robust active sensors and related algorithms for making N recommendations that are appropriately responsive to soil-climate interactions. The objectives of this work were to: 1) determine yield reductions for a given level of N stress at V11-V15 if not corrected with in-season applications, and 2) develop an active sensor algorithm that can be used to translate sensor readings into appropriate in-season N applications that maintain yields relative to optimum levels of preplant applied N. Chlorophyll meter and grain yield data from an ongoing long-term field study (1995-present) were used in conjunction with data from experiments conducted during the 2005 growing season to develop an algorithm for in-season N management. In the 2005 experiments, SPAD and sensor readings were collected throughout the season and grain yield measured at maturity at the three sites. An algorithm for in-season N management based on active sensor readings is proposed. Results indicated that a sensor based sufficiency index (SI_{SENSOR}) at V11 and V15 was linearly related to relative yield when no N was added. Sensors can be used to predict N

status of the crop, and N deficiencies can be corrected depending on the degree of stress using the algorithm developed. A SI_{SENSOR} value of 0.88 was the threshold or critical level for determining whether a relative grain yield of at least 0.94 would be attained, independently of the growth stage at sensing. More research is needed to evaluate if the concept can be used in other areas.

Key words: Active canopy sensors, corn, in season N management.

Chapter 3

A framework for on-the-go nitrogen management in cornfields using active canopy sensors.

INTRODUCTION

Traditional nitrogen (N) management schemes for corn production in the USA have resulted in low N use efficiency (NUE), environmental contamination, and considerable public debate regarding use of N fertilizers in crop production. A major factor contributing to decreased N use efficiency and environmental contamination for traditional corn N management schemes is routine pre-season application of large doses of N before the crop can effectively utilize this N. The long-term research goal at the Nebraska Management Systems Evaluation Area (MESA) site is to reduce these over-applications by using active sensor measurements to direct fertilizer only to areas needing N at times when the crop can most efficiently utilize the N. A major constraint to variable rate in-season N application for corn is having robust active sensors and related algorithms for making N recommendations that are appropriately responsive to soil-climate interactions.

Results from the previous chapter in this dissertation showed a high correlation between SPAD-based and sensor-determined estimates of canopy N status. Thus, it was hypothesized that active sensor assessments of crop N status could be used in lieu of chlorophyll meter readings to diagnose in-season N deficiencies in making variable rate N applications. This chapter also integrates results from an ongoing long-term field study

(1995-present) conducted at the MSEA site, where grain yield and chlorophyll meter data have been collected. Regression analyses performed on the MSEA grain yield and chlorophyll meter data combined over years and growth stages (for chlorophyll meter data) showed that a quadratic model provided a good fit for both chlorophyll meter readings and relative yield in response to increasing N, and indicated that maximum yields occurred at around 175 kg ha^{-1} N over years for this site (Varvel et al., 2006). These results suggest that chlorophyll meter readings during vegetative growth can be used to assess N status variation across a range of environmental conditions and growth stages, and can be used to determine the amount of in-season N required to correct N deficiencies. Based on the collective results from the previous chapter and the MSEA study, it was hypothesized that an algorithm could be developed, incorporating active sensor readings acquired during vegetative growth (V11 – V16), and used in making in-season variable rate N applications. The objectives of this work were to: 1) determine yield reductions for a given level of N stress at V11-V15 if not corrected with in season applications and 2) develop an active sensor algorithm that can be used to translate sensor readings into appropriate in-season N applications that maintain yields relative to optimum levels of preplant applied N.

MATERIALS AND METHODS

Experimental Treatments and Field Design

To address the objectives, plots were established at three separate study sites during the 2005 growing season near Shelton, NE (40.75209N, -98.766W, elevation 620 m above sea level), where N was applied in different amounts and at different times in an

attempt to generate canopies with varying N status. All three studies were conducted within the bounds of the Nebraska Management Systems Evaluation Area (MSEA) project. Studies were designated as south linear (SL), north linear (NL), and Niemack (NK). The soil at all three sites is Hord silt loam (*Fine-silty, mixed mesic Pachic Haplustoll*, 0 – 1% slope). Studies were conducted on fields that had been under sprinkler irrigation with continuous corn for the last 15 years. Corn was seeded on 9 May, 2005 on the SL and NL fields and 25 April, 2005 on the NK field at a target density of 74,000 seeds ha⁻¹. To satisfy the P requirements at all sites, liquid fertilizer (10-34-0) was applied at the rate of 94-liter ha⁻¹ beneath the seed at planting, providing approximately 18 kg ha⁻¹ of P. The crop received irrigation throughout the growing season according to established irrigation scheduling principles. Weed control at all sites was accomplished through a combination of cultivation and herbicide application. Climatological data were recorded through the use of an automated weather station (High Plains Climate Center Network, University of Nebraska) located on the MSEA site. Phenology data according to Ritchie et al. (1992) were recorded weekly from 1 June through mid-August. Accumulated growing degree-days (GDD) were calculated by summing daily GDD's where $GDD = [(T_{MAX} + T_{MIN})/2] - T_{BASE}$, and T_{MAX} is the daily maximum air temperature, T_{MIN} is the daily minimum air temperature, and T_{BASE} was set as 10° C. An upper temperature threshold (T_{UT}) was set at 30° C. Before entering data into Eq. (1), T_{MAX} and T_{MIN} were set equal to T_{BASE} if less than T_{BASE} and were set equal to T_{UT} when greater than T_{UT} (McMaster and Wilhelm, 1997). The starting date for accumulating GDD was planting date in each field.

The SL field plots were part of an ongoing study (1991- present) involving treatments consisting of a factorial combination of four hybrids and five N application levels (0, 50, 100, 150, and 200 kg N ha⁻¹). A split plot arrangement of treatments was used with hybrids as main plots and N levels as subplots with four replications in a randomized complete block design. Sensor data for this study were collected from only two of the four Pioneer brand hybrids (“P33V15”, upright canopy; “P31N27”, planophile canopy). Since hybrid and N treatments had been applied to the same areas from the beginning of the original study, residual soil N levels were low in the control plots (0 kg N ha⁻¹), and crop response to N was assured at this site. Individual plot dimensions were 7.3 by 15.2 m, consisting of eight 0.91-m rows planted in an east-west direction. Nitrogen fertilizer, as 28% UAN solution, was applied shortly after planting.

The experimental design at the NL and NK fields was a randomized complete block (3 reps) with treatments arranged as split-split plots. Factors under study were at-planting N application rates of 0, 45, 90, or 270 kg ha⁻¹, time of in-season N application (V11 or V15), and in-season N rates of 0, 45, 90, 135, or 180 kg ha⁻¹. In-season N application time was assigned to whole-plots, at-planting N application rates to subplots, and in-season N application rates to sub-sub-plots. In-season applications rates were superimposed to all subplots but those receiving 270N at planting (Table 1). Plot dimensions for both sites were 7.3 by 15.2 m, consisting of 8 rows (0.91 m apart). Pioneer brand hybrid “P33G30” was planted at the NL site and “P34N42” was planted at the NK site. The N treatments were applied at the appropriate times as 28% UAN solution. The goal with these treatment combinations was to generate corn canopies

varying in N status at different crop growth stages, including a treatment without N stress (270 kg ha⁻¹ at planting treatment) that would produce varying grain yields as well.

Description of Active Sensor System

The active sensor used in this work was the Crop Circle, model ACS-210, developed by Holland Scientific (<http://www.hollandscientific.com/>) through a Cooperative Research and Development Agreement (CRADA) with USDA-ARS. The sensor operates by generating its own source of modulated light, pulsed at ~ 40,000 Hz, using a single polychromatic light emitting diode (LED) that simultaneously emits light in the visible (amber, 590nm +/-5.5nm) and near infrared (NIR) regions (880nm +/-10nm) of the electromagnetic spectrum. The single-diode approach results in the same exact area of the target being illuminated with each pulse of light. Reflectance of modulated light from the target area back to the sensor is measured with separate photodetectors for each waveband (Detector 1: 400nm to 680nm; Detector 2: 800nm to 1100nm). As such, detector hysteresis is less problematic. The polychromatic light source eliminates the need to alternate radiation sources and allows for higher sampling rates to be achieved. Sensor readings were collected at ten times per second, so each recorded value represents the average of about 4000 individual sensor readings. Photodetection of ambient light by the sensor is rejected at an illumination level of up to 400 W m⁻². The field of view for the sensor is 32 degrees by 6 degrees, giving a footprint of about 7.5 by 60cm at 90 cm from the target. The sensor was calibrated using a 20% universal reflectance panel with the sensor placed in the nadir position above the panel. Sensor amplifiers for each waveband were adjusted so that a value of 1.0 was obtained from the 20% reflectance panel at 90 cm from the target. Final output from the sensor is a pseudo-

reflectance value for each band that allows for the calculation of various vegetation indices.

Acquisition of Sensor Reflectance Data and Conversion to Vegetation Indices

Sensor readings were collected starting on 27 June, which corresponded to the V9 growth stage at SL and NL sites and V11 on NK site. To accomplish this, one active sensor was mounted on an adjustable height platform on a high clearance tractor that allowed for maintenance of constant sensor distance above the target throughout the entire growing season. Sensor height was maintained at 0.8 m above the crop canopy for the plot receiving the highest N rate. Sensor readings were collected via computer as the high clearance vehicle traveled through the plots at 6 to 7 km/hr. Readings were collected with the sensor positioned over the 5th southern row in a nadir view. The sensor was interfaced with a Garmin model 16A DGPS receiver to provide spatial coordinates for all sensor readings. Data were imported into a GIS for georeferencing purposes. An area of interest (AOI) was produced for each plot that corresponded to the plot boundary minus a 1.0-m buffer area adjacent to the plot alleyways. Sensor readings were extracted from the AOI to avoid border effects in each plot. Individual sensor readings within a given plot were then averaged to produce one value for each sensor band per plot. Reflectance values from the amber and NIR bands of the sensor were in turn inputted into the Chl index (CHLI), substituting the amber band for the traditional color band in the equation:

$$\text{CHLI} = (\text{NIR}/\text{Amber}) - 1.$$

Leaf Chlorophyll Content Assessment

Leaf chlorophyll content among treatments was assessed with the model 502 Minolta SPAD chlorophyll meter (Spectrum Technologies, Plainfield, IL) according to

Blackmer and Schepers (1995) on the day of collection of crop canopy reflectance measurements. Prior to the silking growth stage, readings were collected from the most recent fully expanded leaf (visible collar) and after silking the ear leaf was sampled. Measurements were taken midway between the leaf tip and base and midway between the margin and the midrib of the leaf from 30 representative plants selected from the center two rows of each plot, and averaged. Plants unusually close together or far apart or those that were damaged were not sampled.

Grain Yield

At maturity, grain yield was measured with a small plot combine, equipped with an electronic yield monitor that records plot weight, moisture, and test weight on-the-go. The entire length of three central rows of each plot in SL and NK fields were harvested with a combine on October 18, 2005. Grain sub samples were kept in plastic bags, moisture recorded and yields adjusted to 155mg kg⁻¹ moisture. In the NL site, six meters from two center rows were hand harvested on October 17, 2005.

Grain Yield and Chlorophyll Meter Data from Long-Term MSEA Study

The most appropriate sensor position, vegetation index, and phenological growth stage with the greatest sensitivity in assessing variation in canopy greenness were confirmed in chapter 2. Subsequent to that, I was interested in developing a robust algorithm that can be used to convert sensor readings into the appropriate in-season N application rates for various vegetative crop growth stages (V10 through V16). To accomplish this goal I utilized chlorophyll meter and grain yield data from an ongoing long-term field study (1995-present) conducted at the Nebraska MSEA site near Shelton, NE under sprinkler irrigation.

The MSEA study compared corn fertilized at five N rates grown in monoculture and a soybean-corn rotation under a linear-drive irrigation system. For this work, only plots corresponding to the corn monoculture treatment were used. Cropping system whole-plot treatments were arranged in a randomized complete block design with four replications. Cropping system whole-plots are 8-rows wide (7.3 m) and 365.8 m long were split into four corn hybrid subplots, each 91.4 m in length. Hybrid subplots were split into five subplots that are 15.2 m long for five fixed N fertilizer treatments (0, 50, 100, 150, and 200 kg N/ha). Corn was planted each year in late April or early May and N fertilizer treatments were applied shortly after emergence. Pre-emergence herbicides were applied shortly after planting and water was applied throughout the growing season as needed to meet crop demands. Cultivation and post-emergence herbicides were used as needed for weed control throughout the growing season.

At regular intervals during the growing season, usually starting at around the 6- to 8-leaf growth stage, chlorophyll meter readings and phenological development were determined. These measurements were taken at weekly intervals for approximately 6- to 9-weeks during the growing season. At physiological maturity, grain and dry matter yields were measured and yield components determined. Grain and stover samples were analyzed for N content and then crop N uptake and N use were calculated.

Chlorophyll meter and grain yield data from the study described above were integrated to develop a model algorithm. To facilitate combination of chlorophyll meter data across years, readings taken at similar phenological growth stages or heat unit accumulations from each of the years were used to develop an algorithm relating chlorophyll meter readings to yield response.

Statistical Analysis

Grain yield, SPAD readings, and sensor reflectance data were normalized within hybrid and replication to a reference situation (using the highest N rate (200 kg ha⁻¹ in the SL field and 270 kg ha⁻¹ in the NL and NK fields) assumed to be non-N limiting. This procedure was used since some variations were obtained in the actual SPAD reading between hybrids, and between SPAD devices used in different replications. Data normalization also accounts for variations in color and plant architecture among hybrids, which in turn affects reflectance. The SL data were normalized within hybrid and replication to the plot receiving 200 kg N ha⁻¹. The NL and NK data were normalized within replication to the average of plots receiving 270 kg N ha⁻¹ at planting.

For testing, the effect of N rate and time of application on grain yield, an ANOVA was performed on data from each study site using the SAS PROC MIXED procedure. PROC MIXED was also used to fit linear and quadratic models between variables. The NLIN procedure was used to fit quadratic-plateau models between relative yield and sensor estimated N offer for small plots receiving varying amounts of N applied at planting and two in-season growth stages (V11 and V15).

RESULTS AND DISCUSSION

Climatological Conditions

Average temperatures for the 2005 growing season were near the long term average for this location (Figure 1), while the rainfall pattern was somewhat atypical. A total of 215 mm of precipitation was received on 11 May, with 170 mm falling in a five hr period. This intense precipitation event led to some crop emergence problems for the late-planted SL and NL studies, which resulted in the establishment of non-uniform

stands especially at the NL site. The remainder of the season provided relatively average weather and crop yields were near normal at the SL and NK sites, where uniform stands were established. Residual soil N levels for the top 90 cm of the soil profile were quite low at all three sites (Table 2), especially after the 11 May rain event. Overall, the combination of near optimal weather with low residual soil N levels provided favorable conditions for obtaining positive responses in the measured variables (chlorophyll meter and sensor-measurements as well as grain yield) to the imposed N treatments at two of the three study sites.

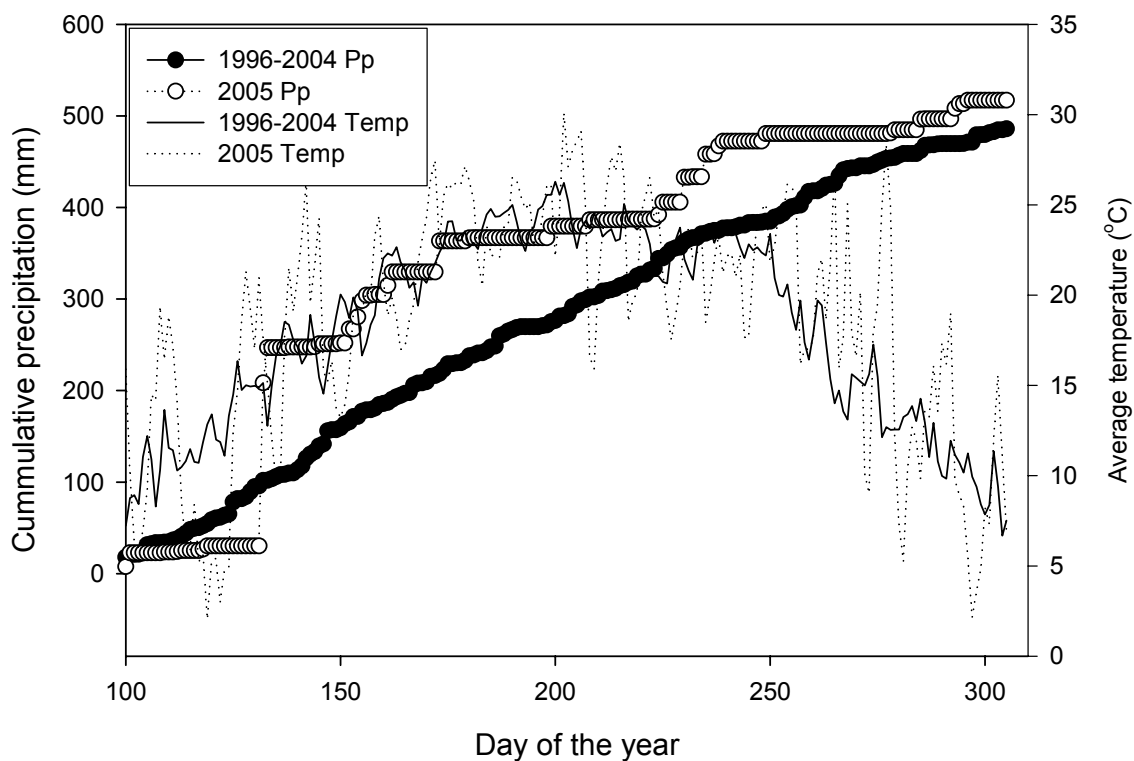


Figure 1: Long term and 2005 average temperatures and cumulative precipitation for the period April-October at the MSEA site, Shelton, NE

Table 1: Incremental N rates applied at various times to generate a degree of N availability on the North linear and Niemack fields. Plots with 270N at planting and no N in-season were considered as non-N limiting and were used as reference plots.

-----V11-----			-----V15-----		
Pre-plant rate	In-season rate	Total N applied	Pre-plant rate	In-season rate	Total N applied
-----Kg ha ⁻¹ -----					
0	0	0	0	0	0
	45	45		45	45
	90	90		90	90
	135	135		135	135
	180	180		180	180
45	0	45	45	0	45
	45	90		45	90
	90	135		90	135
	135	180		135	180
	180	225		180	225
90	0	90	90	0	90
	45	135		45	135
	90	180		90	180
	135	225		135	225
	180	270		180	270
270	0	270	270	0	270
	0	270		0	270
	0	270		0	270
	0	270		0	270
	0	270		0	270

Table 2: Nitrogen and phosphorus content at planting for North Linear and Niemack fields. Nitrogen content after 170 mm of rain is also reported with the May 26 sampling date.

Depth ---cm---	-----May 3-----			-----May 26-----	
	NO ₃ -N	NH ₄ -N	P-Bray1 †	NO ₃ -N	NH ₄ -N
	-----Kg ha ⁻¹ -----				
	North Linear				
0-30	25	13	108	11	15
30-60	17	4		8	10
60-90	21	4		9	14
0-90	63	21		28	39
	Niemack				
0-30	18	16	41	7	17
30-60	5	6		4	13
60-90	3	4		4	15
0-90	26	26		15	45

† P-Bray results correspond to (0-15cm)

Response of Grain Yield and Chlorophyll Meter or Sensor Readings to N

The ANOVA of yield data from the study site (SL field) receiving N only at planting revealed that there was no significant interaction between hybrid and N rate (Table 3), indicating both hybrids responded similarly to N. Grain yields ranged from around 2.08 to 10.61 Mg ha⁻¹ with the addition of N to both hybrids (Figure 2). Grain yield exhibited a quadratic response to increasing rates of N (Table 4), with maximum relative yields achieved around 138.5 kg ha⁻¹ of applied N.

South Linear

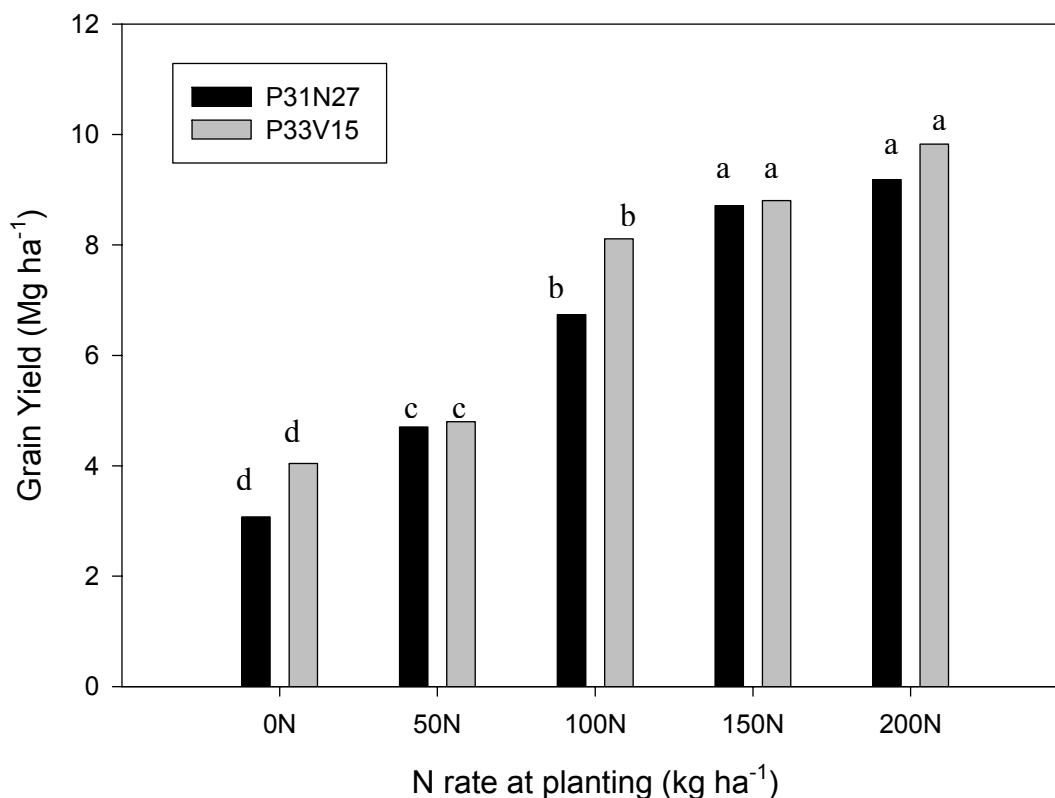


Figure 2: Grain yields in the South Linear field for the 2005 growing season. Similar letters are not statistically different at the 0.05 probability level.

At the NL and NK sites, where varying amounts of N were applied at both planting and in season (V11 and V15), the ANOVA (Table 5) revealed a slightly different yield response to N for the two sites. The interaction between N applied at planting and N applied in-season (V11 or V15) was significant only at the NK site. In general, grain yields ranged from 4.07 to 9.65 Mg ha⁻¹ with N application at the NL site and from 5.97 to 12.11 Mg ha⁻¹ with N application at the NK field (Figure 3a and 3b). At the NK site, yield responses to in-season applied N varied for each at planting N rate, with a different quadratic response function for each at planting rate. Optimum N rates

varied from 135 to 161 kg N ha⁻¹(Table 4). At the NL site, grain yield responses to in-season N rates were all linear (Table 4), indicating that insufficient in-season N was applied to obtain maximum yields. The difference in yield response to N across the two study sites is likely due to the erratic stands at the NL site, which likely minimized the potential for yield response to applied N. Nonetheless, the imposed N treatments created consistent and significant variation in grain yields and in-season canopy N status at SL and NK sites. These variations were determined by both chlorophyll meter and sensor readings presented in the previous chapter, which allow us to successfully address the study objective of developing a sensor algorithm for variable applications of in-season applied N.

Table 3: ANOVA table for yield data for the South linear field 2005

Source	DF	Mean Square	Pr>F
Hybrid	1	10691560	0.0162
N	4	45889941	<0.0001
Hybrid*N	4	1143229	0.2473
Rep (Hybrid)	6	975287	0.3213
Residual	24	786445	

N: N rate applied at planting

Table 4: Relative yield response to N fertilization for the three experiments

Field	Equation	p>F	ONR
South Linear	$RYield_{H1} = 0.2950 + 0.00554 N - 0.00002 N^2$	0.0189	139
	$RYield_{H3} = 0.4560 + 0.00554 N - 0.00002 N^2$		139
Niemack	$RYield_{N_0} = 0.6582 + 0.00322 N_{IS} - 0.00001 N_{IS}^2$	<0.0001	161
	$RYield_{N_{45}} = 0.7356 - 0.002962 N_{IS} - 0.00001 N_{IS}^2$		148
	$RYield_{N_{90}} = 0.8037 - 0.0027 N_{IS} - 0.00001 N_{IS}^2$		135
North Linear	$RYield_{N_0} = 0.83 + 0.000384 N_{IS}$	0.0066	-
	$RYield_{N_{45}} = 0.86 + 0.000476 N_{IS}$		-
	$RYield_{N_{90}} = 0.89 + 0.000567 N_{IS}$		-

H1: Pioneer 31N27, H3: Pioneer 33V15; N_x : N rate applied at planting; N_{IS} : N rate applied in season; ONR: optimum N rate in $kg\ ha^{-1}$

Table 5: ANOVA table for grain yield for the North Linear and Niemack fields 2005.

Source	-----North Linear-----			-----Niemack-----		
	DF	Mean Square	Pr>F	DF	Mean Square	Pr>F
Rep	2	1640154	0.3035	2	422803	0.7018
Ftime	1	8021180	0.0590	1	125769	0.7899
Rep*Ftime	2	714735	0.3922	2	995249	0.3247
Error I						
N	3	11501419	<0.0001	3	37986104	<0.0001
Ftime*N	3	826588	0.3293	3	1194577	0.2864
Rep*Ftime*N	12	714445	0.1437	12	805736	0.0018
Error II						
N_{IS}	4	1727906	0.0090	4	12362230	<0.0001
Ftime* N_{IS}	4	1257714	0.0401	4	78577	0.8936
Ftime*N* N_{IS}	8	1038371	0.0375	8	663585	0.6213
N* N_{IS}	8	803027	0.1163	8	189333	0.0228
Error III	102†	482583		72	267320	

Rep: replication

Ftime: In season fertilization time (eg: V11 or V15)

N: Nitrogen rate applied at planting

N_{IS} : N rate applied in season

† In NL the total numbers of experimental units was 150. After the rain, a copy of the extreme eastern part of the experimental layout was replicated in the western side to avoid any lack of treatment due to emergence problems. Because plant density and distribution were similar all the experimental units were considered.

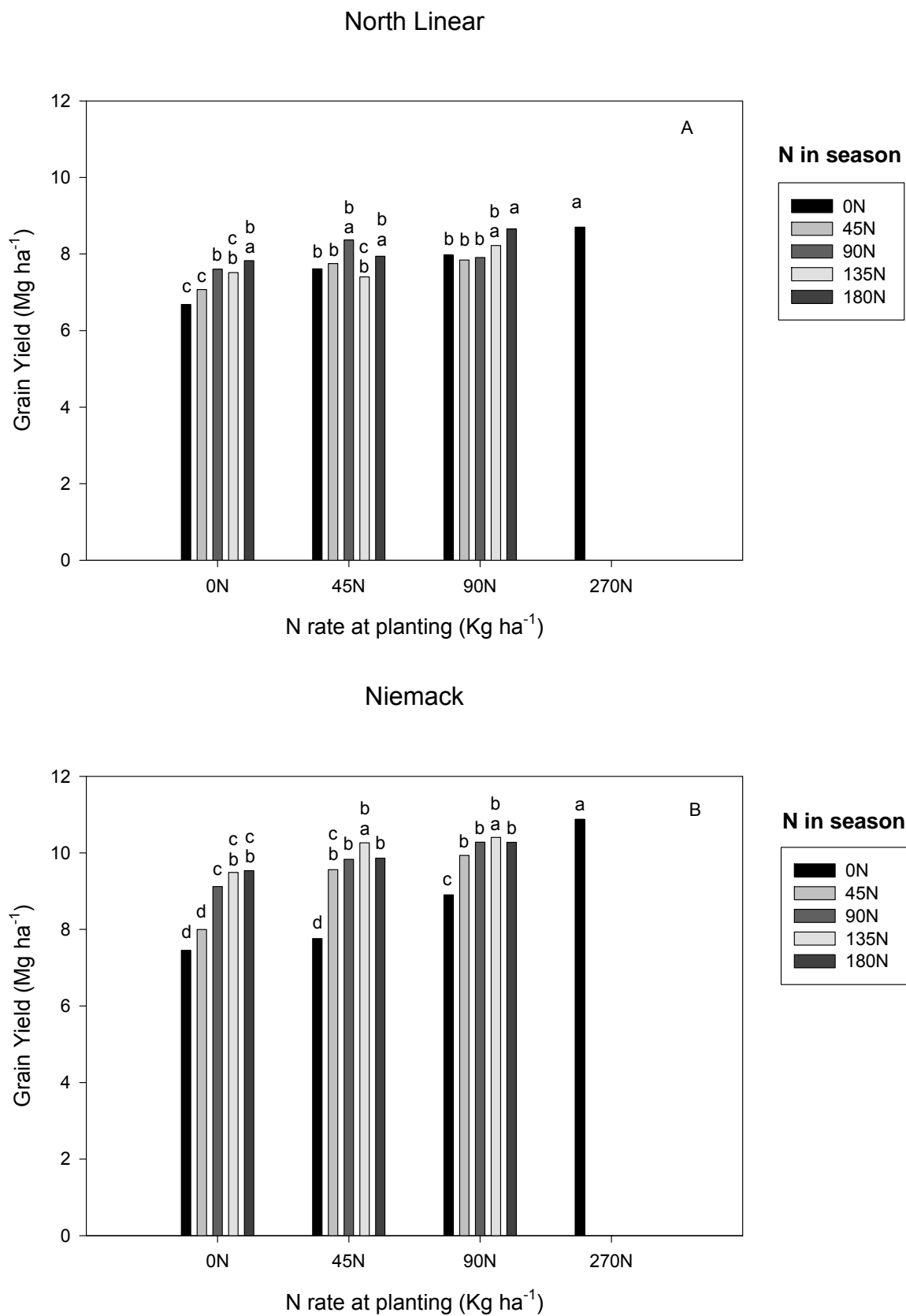


Figure 3: Grain yields in the North Linear and Niemaack fields. Different letters indicate significant differences at the 5% level.

Associations among Chlorophyll Meter and Sensor Readings and Relative Yield

Having confirmed that the N treatments produced significant variability for grain yields as well as chlorophyll meter and sensor readings, the next step was to evaluate the degree of association between the two independent assessments of canopy greenness (chlorophyll meter and active sensor), and then determine if these assessments were associated with N-induced variation in grain yields. In the previous chapter it was established that SPAD and sensor readings were positively associated during the window we propose to make in-season N applications (V11 and V15 growth stages). Chlorophyll meter and sensor-determined assessments of canopy greenness were in turn associated with final grain yield to varying degrees, depending on growth stage and study site (Table 6). It should be noted that for the NL and NK sites, only data from plots receiving N at planting were used to establish this relationship. Plots receiving in-season fertilizer were not used to avoid providing additional yield enhancing N to the crop after sensor readings were acquired. Both chlorophyll meter and sensor-determined indices appeared to have the same ability to predict relative yield within the V11-V15 proposed N application window, as seen by the similar r^2 values for both relationships (Table 6). The only non-significant relation between SI_{SENSOR} and relative yield was for the hybrid P33V15 at the V11 growth stage. However, after tasseling it appears that chlorophyll meter readings are better predictor of relative yield than sensor readings. This is likely due to the presence of the tassels that limit the ability of the SI_{SENSOR} to estimate relative N status, as explained in the previous chapter. Additionally, it should be noted that associations between assessments of canopy N status and grain yield were in general lower for the NL site, where stands were more variable and sensor readings were likely confounded by

influence from the soil back ground. Finally, it is important to note that where the contrast between N treatments was largest (SL field), sensor readings after tasseling were still a good predictor of final grain yield.

Table 6: Coefficient of determination for the linear relationship among SI_{SPAD} , SI_{SENSOR} and relative yield at various crop growth stages. Only the plots receiving N applied planting were used in evaluating these relationships.

Site	GDD	Hybrid	r^2	
			SI_{SPAD}	SI_{SENSOR}
South Linear	500	P31N27	0.38 **	0.61 **
	600	P31N27	0.1 NS	0.45 **
	700	P31N27	0.65 ***	0.66 ***
	800	P31N27	0.69 ***	0.78 ***
	1000	P31N27	0.85 ***	0.56 ***
	500	P33V15	0.60 ***	0.28 *
	600	P33V15	0.71 ***	0.06 NS
	700	P33V15	0.75 ***	0.64 ***
	800	P33V15	0.20 NS	0.54 **
	1000	P33V15	0.56 **	0.67 ***
North Linear	500	P33G30	0.22 NS	0.52 ***
	600	P33G30	0.42***	0.26***
	700	P33G30	0.48***	0.46***
	800	P33G30	0.51***	0.31***
	900	P33G30	0.48***	0.01NS
	1000	P33G30	0.24***	0.05NS
Niernack	600	P34N42	0.75***	0.71***
	700	P34N42	0.84***	0.89***
	900	P34N42	0.70***	0.07NS
	1000	P34N42	0.61***	0.08NS

NS: non significant

*, **, *** Significant at 0.05, 0.01, and 0.001 probability level respectively

Determining Sensor Threshold Values For In Season N Fertilization

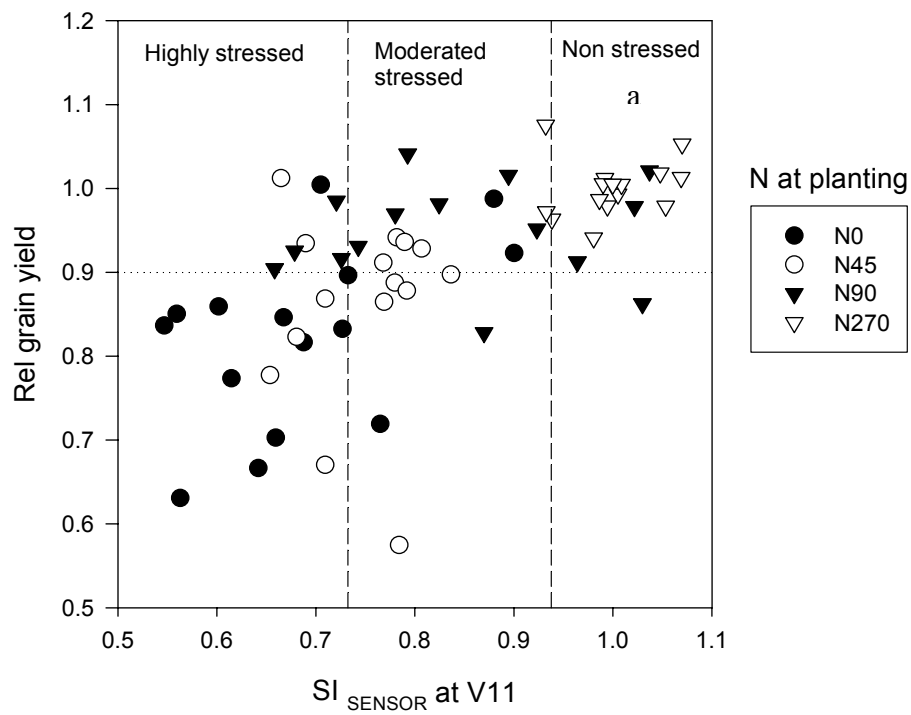
One of the objectives in this work was to evaluate the ability to correct an N deficiency with in-season N application during V11-V15 growth stages. In order to determine if the SI_{SENSOR} value can somehow be associated with the ability to detect and correct an N deficiency, the yield response to the five N rates imposed at V11 or V15 generating a degree of N availability to the crop was evaluated. The ANOVA (Table 5) did not indicate a significant difference in grain yield between mid season time of fertilization (V11 vs. V15). However, chances are that non-significant effects were due to a lack of degrees of freedom for the error term (only 2). Under limited N availability, the development of N stress is progressive during the season. For the NK experiment, 46% of the plots receiving N at V11 exceeded the 0.9 relative yields and 26% exceeded 0.94 relative yields. On the other hand, only 40% of the plots fertilized at V15 yielded more than 0.9 in relative terms and only 15% more than 0.94. For the NL site, 48% of the plots reached 0.9 relative yields regardless of the time of in-season fertilization. Nitrogen shortage diminishes grain yield because it reduces both kernel number and kernel weight. During the vegetative growth period (V6-VT), the corn plant is expanding leaves, elongating nodes and differentiating flowers and ears. After tasseling neither the leaf area nor the potential number of kernels can be increased (Ritchie et al., 1992). The effect of N stress on potential kernel number has been contradictory. For example, accordingly to Lemcoff and Loomis (1986) the potential kernel number of the uppermost ear has been shown to be relatively insensitive to N starvation. However, Jacobs and Pearson (1991), and Brandau and Below (1992) reported significant reductions in spikelets per ear under N stress. Assimilate supply to the ear during the period 2 weeks before silking and 3

weeks after silking is highly associated with kernel number (Tollenaar, 1977; Kiniry and Ritchie, 1985; Tollenaar et al., 1992; Uhart and Andrade, 1995). Nitrogen shortage affects assimilate supply to the ear because it reduces leaf area index, leaf area duration, photosynthetic rate (Novoa and Loomis, 1981; Lemcoff and Loomis, 1986; Sinclair and Horie, 1989; Connor et al., 1993) and therefore, radiation interception and radiation use efficiency (Uhart and Andrade, 1995). Uhart and Andrade (1995) also reported a reduction on dry matter partitioning to reproductive sinks. Therefore, the longer the period under stress and the greater the stress, the more negative impact on total potential number of kernels set per ear, and in turn grain yield. If N stress persists after silking, both number of kernels (Cirilo and Andrade, 1994) and grain weight will be negatively affected (Cirilo and Andrade, 1996). Scharf et al. (2002) found little evidence of irreversible yield loss when N applications were delayed as late as V11, but the risk of yield reductions increased when applications were postponed until silking.

To further understand what SI_{SENSOR} values corresponded to an unrecoverable N stress, SI_{SENSOR} readings collected on all the plots for both fertilizer application dates (V11 and V15) were plotted versus their respective grain yield values for both growth stages at the NK site (Figure 4a and 4b). Sensor readings were arbitrarily assigned to three regions as follows: a value >0.93 was chosen for the non-stressed region because it was the lowest SI_{SENSOR} value for the 270N plots. Then, the remaining population was split into two regions and assumed to be highly early stressed ($SI_{\text{SENSOR}} < 0.73$), and moderately stressed (SI_{SENSOR} from 0.73 to 0.93). At the V11 growth stage, 80% of the plots receiving 0N at planting, 40% of the 45N, and 26% of the 90N fell in the high-early stressed region; 20% of the 0N, 40% of the 45N, and 60% of the 90N fell in the

moderated stress region; and 30% of the 90N and 100% of the 270N were considered non-stressed (Figure 4a). At V15, 100% of the 0N plots fall in the high-early stress region; all the 45N and 90N fall in the moderated stress region, and all of the 270N were non-stressed. Of the plots sensed and fertilized at the V11 growth stage, 33% of the highly stressed, and 61% of the moderately stressed were able to recover and still maintain a relative yield higher than 90% after N fertilizer application was made. All but one (90 at planting + 0N in-season) plot of those classified as non-stressed at V11 had a relative yield higher than 90%. Based on these observations, it appears that for this particular environment 90N applied at planting (~120N including residual soil N from the top 30cm at planting) was adequate to sustain the crop until V11 with a limited degree of stress that could be corrected with an in-season N application. Conversely, 53% of the plots receiving 45N at planting had a relative yields lower than 90% even if they were under moderate stress at the V11 growth stage. For those plots sensed and fertilized at V15, 93% of the plots considered as highly stressed, and 47% of the moderately stressed yielded less than 90% of the average of the non-stressed plots. Nonetheless, only 60% of the plots with 90N applied at planting surpass the 90% relative yield mark.

V11 Niemack



V15 Niemack

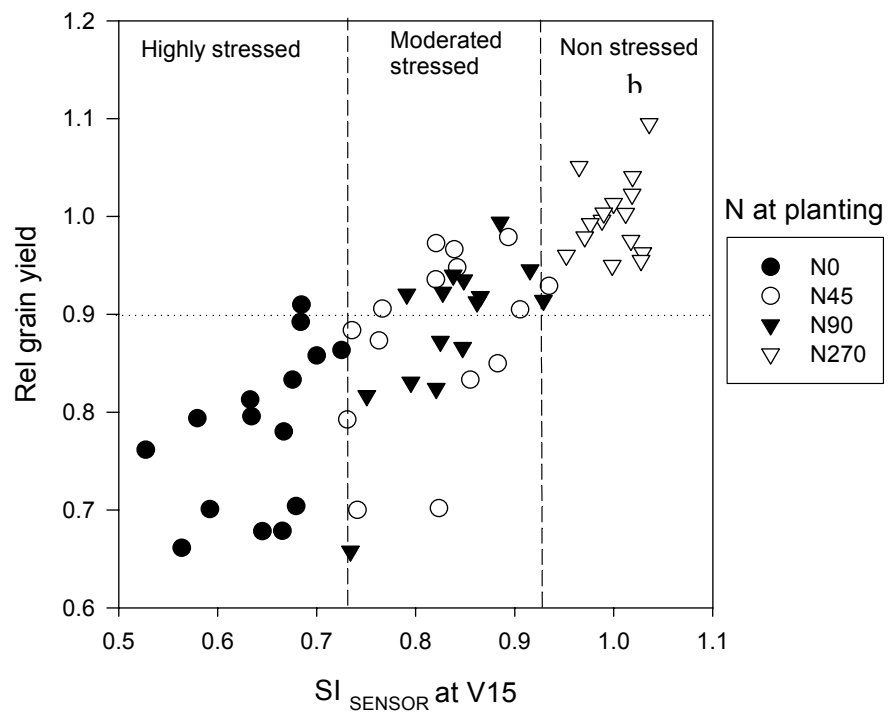


Figure 4: Association between relative grain yield and sensor based sufficiency index (SI_{SENSOR}) for the plots sensed and fertilized at V11 (4a) and sensed and fertilized at V15 (4b).

Figures 5a and 5b illustrate how the ability for correcting N stress with in season N applications is conditioned by N availability or degree of N stress. A Cate-Nelson plot of SI_{SENSOR} values versus relative grain yields for the NK field indicated that a SI_{SENSOR} value of 0.88 was the threshold or critical level for determining whether a relative grain yield of at least 0.94 would be attained, independently of the growth stage at sensing (Figure 5). A value of 0.94 as target relative yield was chosen because of two reasons: it minimized the number of outliers in the upper left and lower right quadrants, and it corresponds to the lower relative yield of the non limiting N treatments. Using this threshold value, 18 points were classified as outliers. Situations like these in the lower right quadrant are what farmers want to avoid. In this experiment, they are explained by a relative high N availability at sensing and a shortage of N after this moment. All the points but one in the lower right quadrant had either 45 or 90N at planting which may explain the relative high SI_{SENSOR} value at sensing. However, 5 out of 7 plots had 135N or less total applied, which might explain the low yield. One of the plots received 90N + 90N. Chances exist that this plot correspond to a sandy patch and N was lost out of the system. Of those points in the upper left quadrant, 10 out of 11 points had at least 135N of total N applied. An interesting observation is that 6 of these 11 points correspond to the V11 fertilization event (Figure 5a), suggesting that the ability of using active sensors to detect N stress and maintain or improve grain yields with in-season fertilization would

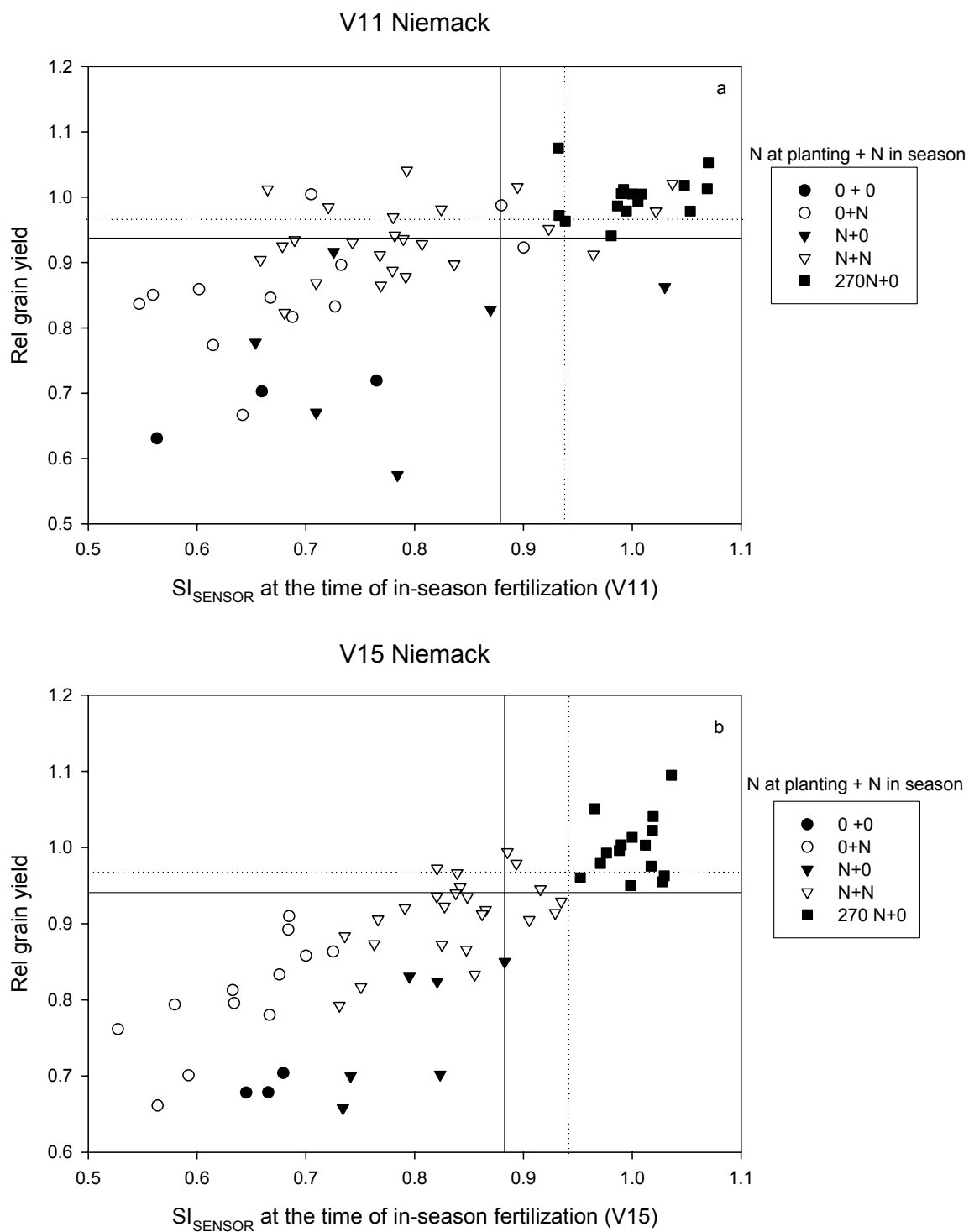


Figure 5: Scatter diagrams of corn relative yield versus sensor based sufficiency index at a) V11 and b) V15 at the Niemack field. The vertical lines show the threshold value for a relative yield of 94% (solid) and 97% (dotted) using a Cate-Nelson analysis.

increase if working closer to V11 than tasseling. Most farmers however, would only accept a 2-3% yield reduction for a new technology unless it increases profitability. For a 97 and 98% relative yield, the SI_{SENSOR} value was found to be 0.94 and 0.96 respectively. In this case, 10 out of the 17 plots with a combination of at- planting and in- season N fertilization in the upper left quadrant were fertilized at V11 supporting the idea of applying N closer to V11 than to pre- tassel.

Development of a Sensor Algorithm for In-season N Fertilization

A reactive approach to N fertilization management must rest on the ability to accurately detect crop N stress in a timely manner. The major challenge in making N fertilizer recommendations is that future weather cannot be accurately predicted. In addition, a SPAD reading value is an indication of the severity of a stress at a given time, and does not provide information about how much can we expect for the remaining of the season. However, having 10 years of SPAD and yield data tends to integrate the effect of climate variability in both soil N supply and crop N needs (Johnson and Raun, 2003). A SPAD based sufficiency index (SI_{SPAD}) can be used as an indicator of crop N status (Blackmer and Schepers, 1995; Piekielek et al., 1995; Bausch and Duke, 1996; Jemison and Lytle, 1996; Waskom et al., 1996; Sunderman et al., 1997; Varvel et al., 1997). Moreover, in chapter 2 a linear relation between a SI_{SPAD} and sensor- based sufficiency index (SI_{SENSOR}) was found. These findings encouraged us to translate what we know about in- season N management using SPAD meters to a sensor-based technology. Figures 6 and 7 depict the concept for our sensor-based recommendation framework for N fertilization. Corn yield and SPAD meter data from a long term study at the Nebraska MSEA site (Varvel et al., 1997) corresponding to the period 1995-2004 were used to

estimate the relationships between 1) N availability at planting and relative yield, 2) SPAD based sufficiency index (SI_{SPAD}) and relative yield, and 3) soil N availability and SI_{SPAD} . The only concern with using these data arose when the difference in absolute yields for the 0N checks between the SL field ($\sim 2.5 \text{ Mg ha}^{-1}$) and the NL and NK fields for the 2005 growing season ($>6 \text{ Mg ha}^{-1}$) were considered; in that for similar soils, a systematic depletion of N over more than 10 years may introduce changes in the system that may not correspond with commercial cornfields. However, considering that farmers will work in the proximity of N sufficiency it was decided to use the MSEA data.

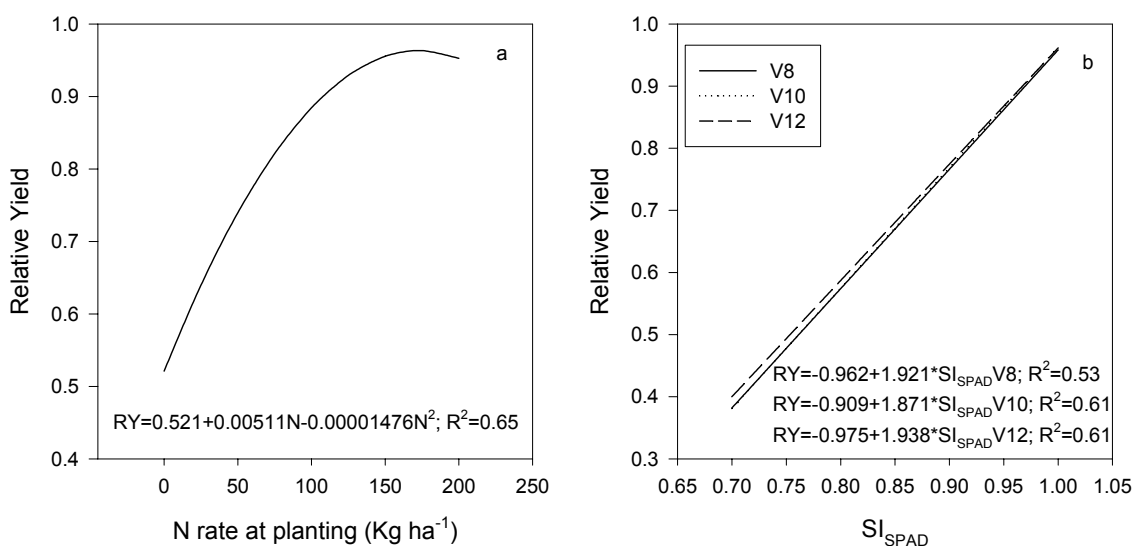


Figure 6: Response for a) Relative yield vs. N rate at planting for all years of long-term MSEA study, b) SPAD based sufficiency index at the V8, V10 and V12 growth stages vs. relative yield for all years of long-term MSEA study.

Results from the regression analyses performed on the MSEA grain yield data combined over years (1995-2004), with maximum yields ranging from 10.4 to 13.6 Mg ha⁻¹, showed that a quadratic model provided the best fit for relative yield response to N ($r^2 = 0.65$), and indicated that maximum yields occurred at around 175 kg ha⁻¹ N for this site (Figure 6a). The quantity is similar to the value Dobermann et al., (2006) reported for a study where N responses were evaluated across 34 sites in Nebraska from the 2002-2004 period. In addition, the relation between the chlorophyll meter sufficiency index readings and relative yield for the MSEA data was found to be linear and growth stage specific (V8, $r^2 = 0.53$; V10, $r^2 = 0.61$; V12 $r^2 = 0.61$; Figure 6b). As expected, the chlorophyll meter sufficiency index readings also exhibited a quadratic response to N (Fig. 7a) with a model r^2 value of 0.70 for data analyzed over years and growth stages. These results suggest that chlorophyll meter readings during vegetative growth can be used to assess N status variation across a range of environmental conditions and growth stages and determine amount of in-season N required to correct an N deficiency. For example, using the function in Fig. 7a, the amount of N needed to correct an N deficiency at a sufficiency index of 0.90 is around 125 kg N ha⁻¹, knowing 175 kg N ha⁻¹ produced maximum yields. In a refinement of our concept we tested the hypothesis that the best fitting models varied with growth stage.

Even though the previous discussion indicated that one quadratic function provided a reasonably good fit for the chlorophyll meter data combined across years and growth stages, I used SPAD data available for 600GDD and 700GDD to construct chlorophyll meter algorithms for this work since it corresponds with our proposed window of N fertilizer application (V11-V15). Data were normalized within hybrid,

replication and year. The entire set of data (four hybrids per year and ten years) was plotted against N rate (Figure 8a) and a model was fitted that can be used to estimate the amount of soil N available for the crop at a given growth stage as follows:

$$SI_{SPADV11} = 0.7982 + 0.00211 N - 0.00000585 N^2; R^2 = 0.75^{***} \text{ [Eq 3]}$$

$$SI_{SPADV15} = 0.7914 + 0.00230 N - 0.00000680 N^2; R^2 = 0.73^{***} \text{ [Eq 4]}$$

Our sensor results reported in chapter 2 showed that variation in canopy greenness, expressed as the Chl index, was highly associated with independent assessments of canopy greenness by the SPAD meter (Figure 8b). These relationships were found to be growth stage specific as follows:

$$SI_{SPADV11} = 0.4794 SI_{SENSOR V11} + 0.5043; R^2 = 0.77^{***} \text{ [Eq 5]}$$

$$SI_{SPADV15} = 0.6903 SI_{SENSOR V15} + 0.2981; R^2 = 0.88^{***} \text{ [Eq 6]}$$

These results indicate that active sensor readings can be used in lieu of chlorophyll meter readings to measure how much in-season N to apply.

Using equation 3 and 5 or equation 4 and 6, $N_{ESTIMATED}$ can be calculated, respectively, as:

$$N_{ESTIMATED V11} = \{-0.00211 - [0.000004452 + 0.0000234 * (0.798 - (0.4794 SI_{SENSOR V11} + 0.5043))]^{1/2}\} / (-0.0000117) \text{ [Eq 7]}$$

$$N_{ESTIMATED V15} = \{-0.00230 - [0.00000529 + 0.0000272 * (0.791 - (0.6903 SI_{SENSOR V15} + 0.2981))]^{1/2}\} / (-0.0000136) \text{ [Eq 8] (Figure 8c)}$$

If we assume 100% efficiency for in-season N applied, it follows that the amount of N we need to apply to maximize yield for a given year (N_{IN_SEASON}) will be

$$N_{IN_SEASON} = 175 \text{ (kg/ha)} - N_{ESTIMATED} \text{ [Eq. 9]}$$

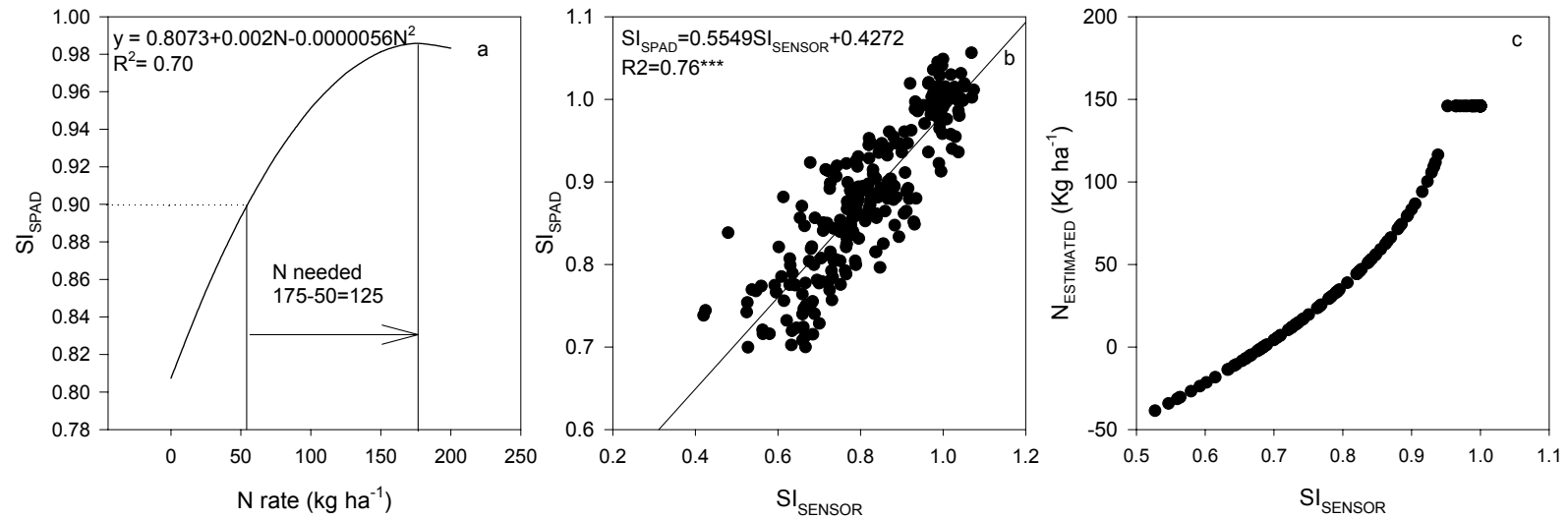


Figure 7: Response for a) SPAD sufficiency index readings (SI_{SPAD}) vs. N rate for V10 through V16 staged corn for all years of long-term MSEA study), b) sensor based sufficiency index vs. SI_{SPAD} . SPAD sufficiency index and sensor readings were collected at two (V11 and V15) growth stages for corn receiving varying amounts of N applied at planting and two in-season (V11 and V15) growth stages in 2005. c) Estimated N in the system ($N_{ESTIMATED}$) using SI_{SENSOR} and equation derived from figures 6a and b.

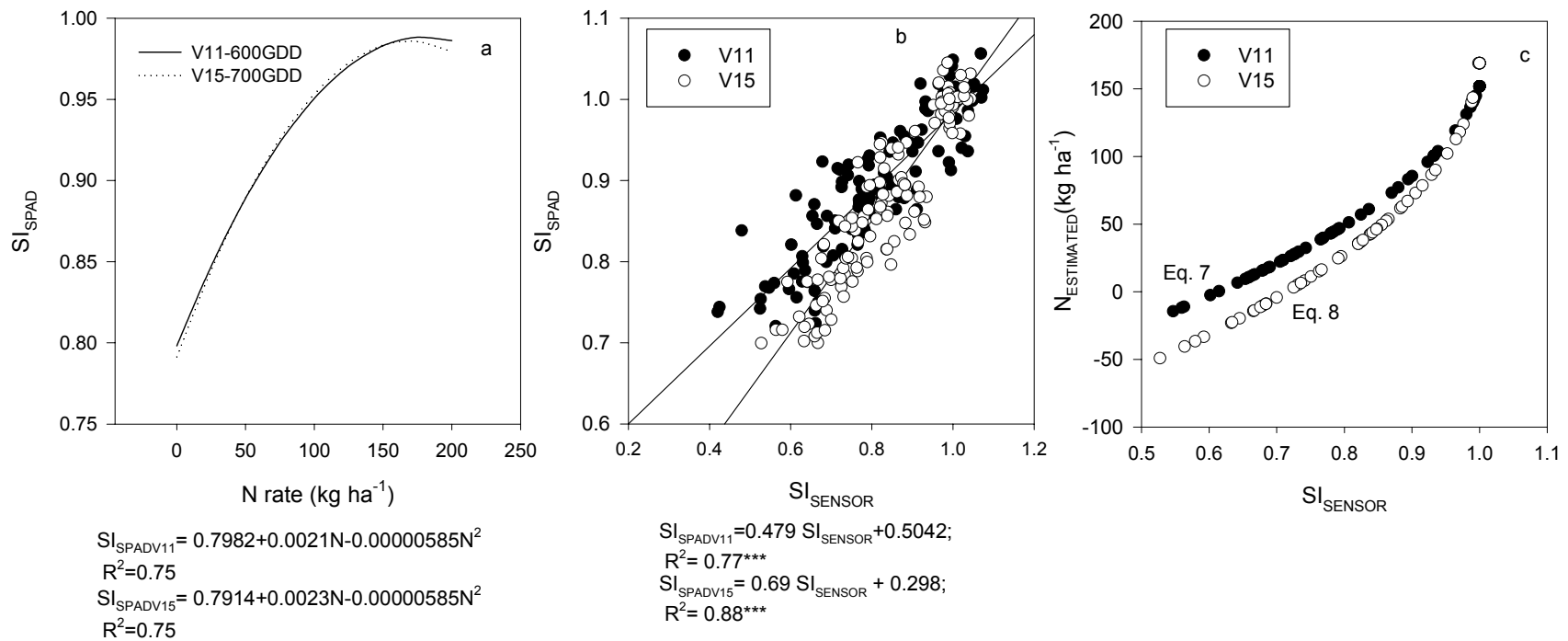


Figure 8: Response for a) SPAD sufficiency index readings vs. N rate for V11 and V15 staged corn for all years of long-term MSEA study), b) sensor based sufficiency index vs. SPAD based sufficiency index. SPAD sufficiency index and sensor readings were collected at two (V11 and V15) growth stages for corn receiving varying amounts of N applied at planting and two in-season (V11 and V15) growth stages in 2005. c) Estimated N in the system ($N_{ESTIMATED}$) using SI_{SENSOR} and equation 7 and 8.

Calibration of Sensor Algorithm

As previously mentioned, the intense rainfall event soon after planting resulted in erratic plant stands at the NL site, affecting yield response to N and variability in sensor readings. Therefore, only data from the NK site were used to verify the algorithm. Two approaches were tested. The first was a growth stage specific model using equations 3 and 5 to estimate N ($N_{ESTIMATED}$) at V11, and equation 4 and 6 with the same purpose at V15. Then, $N_{SUPPLIED}$ was expressed as $N_{IN-SEASON}$ (eq. 9) minus N actually applied at the NK field at each growth stage, and plotted $N_{SUPPLIED}$ vs. relative yield. The second was to use the equations calibrated across growth stages (as in Figures 7a and 7b) to calculate $N_{ESTIMATED}$, and then following the same steps, plotted $N_{SUPPLIED}$ vs. relative yield. In both cases quadratic- plateau models fit the data (Table 6). A joint value for the two sections near 0 kg N ha^{-1} would indicate the adequacy of the model to estimate the N supplied and available to the crop for maximizing yield. The quadratic portion of the model indicates that N deficiency can be corrected with in season N application at the V11 and/or V15 growth stages depending on the degree of N stress. The plateau points out that more than enough N was available for many plots but this N was not utilized to increase grain yield. There are many ways for N to be lost after the fertilization. Among them are leaching (Schepers et al., 1991; Zhu and Fox, 2003), denitrification (Hilton et al., 1994), volatilization of fertilizer applied (Fowler and Brydon, 1989), volatilization of NH_3 direct from the crop (Francis et al, 1993), all of which reinforce the idea that NUE can be improved by time and site- specific agronomic actions. However, the parameters for the growth stage specific approaches did not differ between growth stages (Table 6).

Table 7: Parameters for the quadratic-plateau models for the Niemack field. The form of the model is shown in figures 8a and 8b

Model	R ²	X ₀	plateau	-----Parameters of the model†-----		
				-----a-----	-----b-----	-----c-----
GSS‡						
V11	0.57***	-10	0.96	0.9577 ± 0.0204	-0.00024 ± 0.000720	-0.00001 ± 4.34E-6
V15	0.68***	-13	0.95	0.9434 ± 0.0162	-0.00025 ± 0.000537	-9.61E-6 ± 2.962E-6
V11-V15	0.63***	-9	0.95	0.9515 ± 0.0120	-0.00018 ± 0.000411	-9.94E-6 ± 2.37E-6
AGS§						
V11-V15	0.63***	-11	0.95	0.9503 ± 0.0135	-0.00023 ± 0.000447	-9.89E-6 ± 2.47E-6

†: Estimates ± Standard error
‡: Growth stage specific approach
§: Across growth stage approach

Hence we pooled the data and fit a single model that relates N_{SUPPLIED} and relative yield (Figure 9a). The parameters for this model were not statistically different from our second approach model (Table 6, Figure 9b). The r^2 values for each case were similar, and the parameters for the quadratic term were not different among models (Table 5). We know that the relations between SI_{SPAD} and N supplied at planting (Figure 8a), and between SI_{SPAD} and SI_{SENSOR} (Figure 8b) were growth stage specific. This makes sense, since the development of N stress during the season is a gradual process. Chlorophyll production will be affected before a change in biomass production can be detected. Hence, we expected the models to be growth stage specific. However, this was not the case. A possible explanation might be that the regressions lines in both cases cross each other around the maximum rate applied and/or relative values ~ 1 . Therefore, the growth stage specificity of the SI_{SENSOR} becomes diluted when SI_{SENSOR} approaches to 1 or, in other words, when N stress decreases.

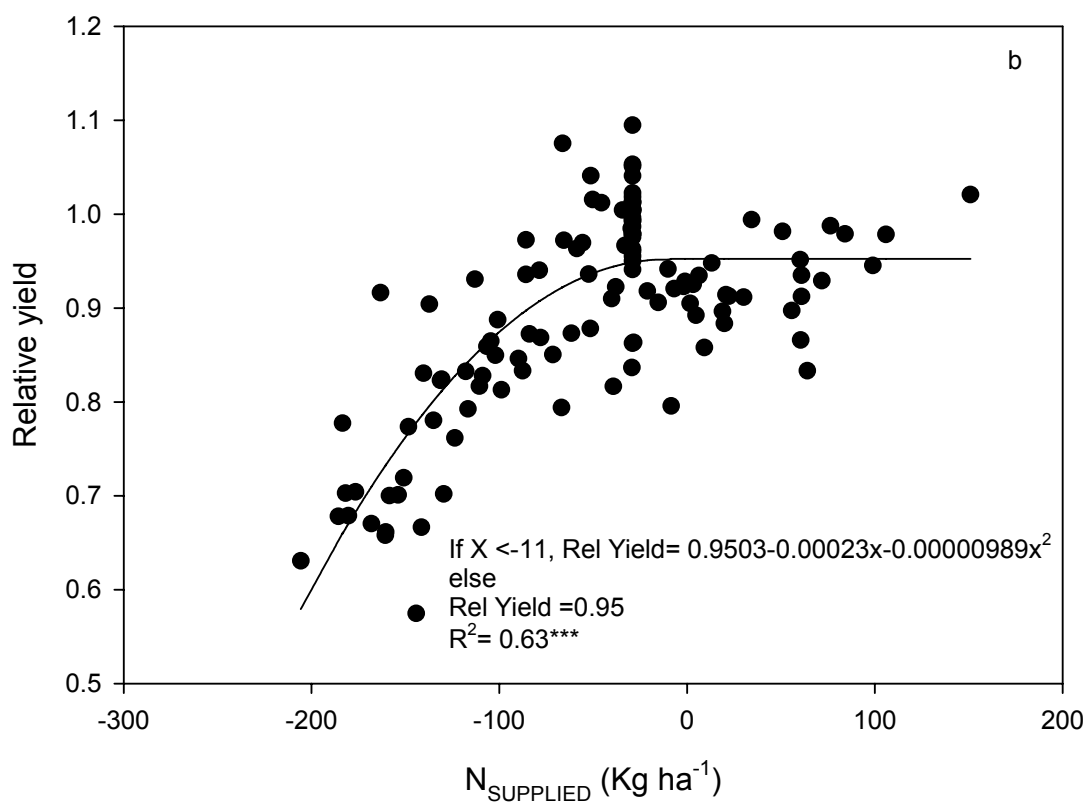
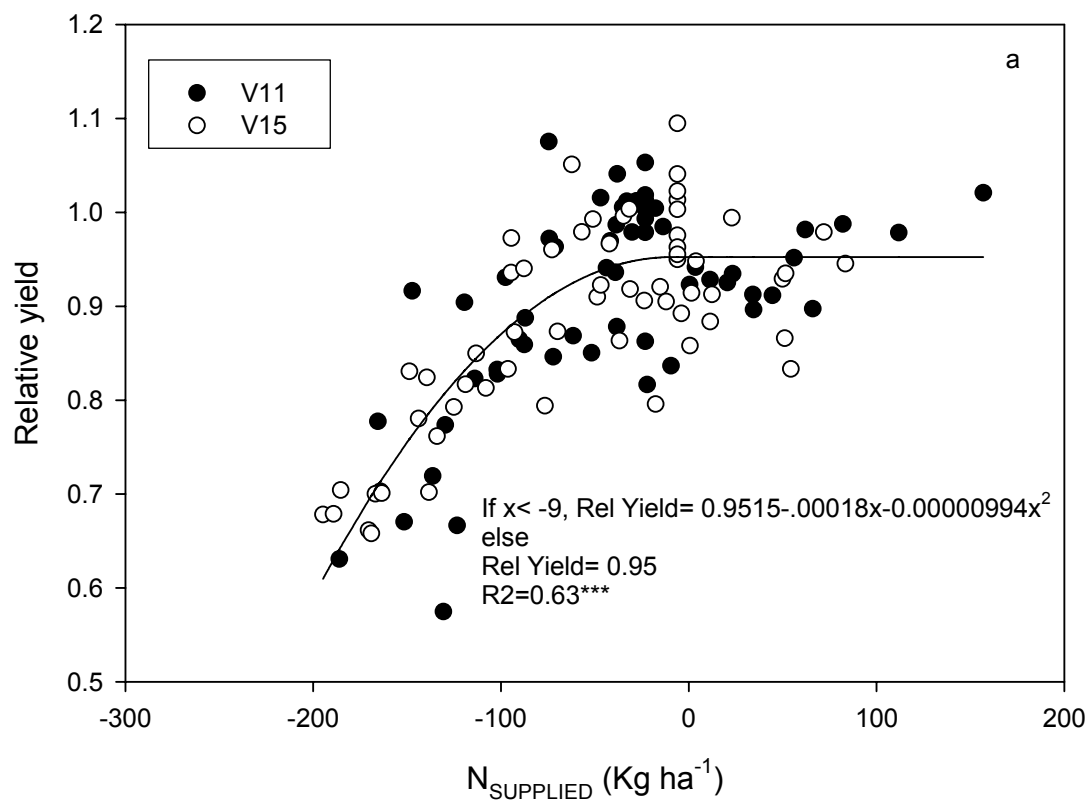


Figure 9: Relative grain yield vs. sensor-estimated N_{SUPPLIED} for small plots receiving varying amounts of N applied at planting and two in-season growth stages (V11 and V15) in the NK field, 2005. Sensor estimated N need was determined by first collecting sensor readings for each plot on the day N was applied (V11 or V15), and converting sensor readings to Chl index. The Chl index value of a given plot was converted to N status (kg N ha) relative to the 175 optimal N rate, using the relationships between N application vs. sufficiency index, and sufficiency index vs. sensor Chl index as shown in equations 5 to 8. Figure 9a shows the model fitted using the growth stage specific equations. Figure 9b depicts the model fitted using the equations calibrated across growth stages.

SUMMARY AND CONCLUSION

In this chapter an algorithm for in season N management based on active sensor readings was proposed. We found first that sensors can be used to predict N status of the crop. Second, N deficiencies can be corrected depending on the degree of stress. In general, treatments without N at planting did not yield more than 0.90 relative yield, regardless the amount of N applied in-season; but plots with 45N or 90N at planting were able to recover if enough N was applied in a timely manner. Third, a $SI_{\text{SENSOR}} < 0.78$ during the period V11-V15 may indicate an irrecoverable yield loss of ~10%. Assuming that the farmers will not tolerate a yield loss bigger than 3%, the threshold level for SI_{SENSOR} increases up to 0.94. At this point the algorithm is site- specific since the data was collected in the same MSEA site, and needs to be validated. Climate as well as soil N residual levels may affect the relative risk of yield losses with delayed N applications. Therefore, more research is needed to evaluate if the concept can be used in other areas

under different soil and climatic conditions; and if the equations 5 and 6 (one hybrid and one year of data) need to be tuned.

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SUMMARY

The objective of this work was to develop a reflectance based technology for in-season and on-the-go management of N fertilization in irrigated cornfields. An active sensor algorithm was developed to translate sensor readings into appropriate in-season N applications that maintain yields relative to optimum levels of pre-plant applied N.

As a first step, a series of experiments was conducted with the objectives of calibrating two active sensors, and understanding how different operational issues may affect sensors' outputs. Fundamental information was retrieved from these experiments: first, sensitivity limitations prompted us to work between 60 and 110 cm over the canopy with the Crop Circle sensor and between 80 and 110 cm for the GreenSeeker sensor. It is important to note that vegetation indices involving a ratio of reflectance values (i.e., NIR/amber) are largely immune from the effect of distance between the sensor and target, but reflectance data from the individual bands are not. Therefore, variability in data from the NIR band for example, can be due to either distance between the sensor and top of the canopy or the amount of living vegetation in the field of view. Normalizing data from several bands removes the effect of distance because both are affected the same. Second, sensitivities of the vegetation indices evaluated for biomass estimation did not improve by orienting the sensors at a 45° angle at V10. Third, special effort should be made to keep the sensor directly over the row while driving in the field. Vegetation index values for both sensors decreased as they moved from over the row to between the rows at V7; and displacing the sensors by 10 cm from the center of corn rows at V10 underestimated NDVI for the GreenSeeker sensor by 51 % and 3% for the Crop Circle sensor. Finally, although NDVI calculations are particularly indicative of biomass, N deficiency could be

detected from V7 to V16. Because the Crop Circle sensor showed less electronic noise than the GreenSeeker sensor and provides individual waveband information that allows for calculation of different vegetation indices, it was selected for further development of this technology.

In a first approximation, it was hypothesized that active crop canopy sensors could be used for on-the-go measurement of relative chlorophyll status in irrigated cornfields. Therefore, experiments were conducted to determine 1) the most appropriate phenological growth stages, and 2) the vegetation index that had the greatest sensitivity to evaluate corn canopy greenness or N status. Active sensor readings were compared to chlorophyll meter readings throughout the season in three fields where N treatments induced a range in leaf chlorophyll content. Our results indicated that the Crop Circle sensor provided information not only about relative chlorophyll content but also about plant distribution and biomass. The four vegetation indices evaluated were linearly related with chlorophyll meter readings during the vegetative growth stages. The wide dynamic range vegetation index, chlorophyll index, and amber ratio showed more sensitivity than NDVI to variations in relative chlorophyll content. During reproductive growth stages it seems that the presence of the tassel in the sensor's field of view impaired the ability of the device to detect variations in chlorophyll content of the crop.

Based on these results it was hypothesized that active sensor assessments of crop N status could be used in lieu of chlorophyll meter readings to diagnose in-season N deficiencies in making variable rate N applications during the V10 to pre tassel period. To address the objectives, chlorophyll meter and grain yield data from an ongoing long-term field study (1995-present) conducted at the Nebraska MSEA site near Shelton, NE

under sprinkler irrigation were used to calibrate the relation between a SPAD based sufficiency index and relative yield. In addition, plots were established at three separate study sites during the 2005 growing season, where N was applied in different amounts and at different times in an attempt to generate canopies with varying N status. Results indicated that a sensor based sufficiency index (SI_{SENSOR}) at V11 and V15 was linearly related to relative yield when no in-season N was added. Sensors can be used to predict N status of the crop, and N deficiencies can be corrected depending on the degree of stress using the algorithm developed. A SI_{SENSOR} value of 0.88 was the threshold for determining whether a relative grain yield of at least 0.94 would be attained, independently of the growth stage at sensing. For a 97 and 98% relative yield, the SI_{SENSOR} value was found to be 0.94 and 0.96 respectively. In this experiment, 90N applied at planting was enough to take the crop until V11 with a limited degree of stress, which was corrected when enough N was applied in-season. However, 90N at planting was not always enough when in-season applications were delayed until the V15 growth stage.

The results obtained show promise for using active sensor technology to monitor crop N status and deliver N fertilizer in the amount and location needed by the crop. In this way, using the Crop Circle sensor and a variable rate system during the V10 to pre tassel period allowed us to tackle the three major causes of low NUE: 1) poor synchrony between soil N supply and crop demand, 2) uniform fertilizer N applications to spatially-variable landscapes that commonly have spatially-variable crop N need, and 3) failure to account for temporal variability and the influence of weather on mid-season N needs.

Nonetheless, more research is needed in order to validate these results in a wider range of soil and climatic conditions.