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Utilizing NDVI and remote sensing data to identify spatial variability in plant stress as influenced by management

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CHAPTER I: GENERAL INTRODUCTION

Environmental stress can impose losses in modern agricultural production systems (Boyer, 1982). Identification of an effective yet practical tool to identify and evaluate areas of plant stress is needed. Understanding the spatial distribution of environmental stress in fields and the resulting growth penalties can allow for changes in management practices. Remote sensing and precision agriculture technologies provide an opportunity to evaluate plant communities using light reflectance (Hatfield et al., 2008). The evaluation of current methods used to interpret plant growth over a variety of constraints, provided here, will further the implementation of remote sensing techniques for managing field crops.

The goal of plants grown in a natural environment is to productively reproduce (Boyer, 1982). Agriculture defines the success of a plant as productivity per unit of land area. Environmental stresses impose limitations on plants ability to achieve maximum yield. Inadequate fertility can reduce the growth and production of corn (Eck, 1984; Jacobs et al., 1991). Dry conditions and high temperatures impede corn growth and development, impacting transpiration and nutrient uptake (Fulton 1970; Herrero et al., 1980; Dwyer, et al. 1992; Crafts-Brandner et al., 2002). The consequence of stressful growing conditions is a decline in leaf chlorophyll concentrations, a decrease in incident light absorbance, and a reduction in overall plant productivity (Carter, 1993; Masoni et al., 1996; Carter et al., 2001; Zhao et al., 2003). Boyer (1982) estimated only 12.1 percent of the land surface is free from environmental constraints. Mitigating risks associated with crop production by identifying and managing the limitations of plant productivity spatially is essential for agricultural success.

Remote sensing techniques provide a platform for which plant stress and growth response can be evaluated. Sensors have been developed to measure the reflectance of incident light at various wavelengths and have been related to plant growth and vegetative cover. The use of vegetative indices has allowed users to relate differences in reflectance to changes in canopy characteristics (Hatfield et al., 2008). There are numerous indices, all derived from ratios based on the reflectance of incident light at specific wavelengths. The normalized difference vegetative index (NDVI) has gained wide acceptance based on its ease of use, only requiring two wavelengths, and the plant characteristics it has been correlated too. NDVI has been used to evaluate plant nitrogen status, chlorophyll content, green leaf biomass and grain yield (Ma et al., 1996; Shanahan et al., 2001; Shanahan et al., 2003; Solari et al., 2008). Spectral information has been used to evaluate micronutrient stress, detection of insect infestation, and disease infection of plants (Printer et al., 2003). A primary objective of this study was to explore the potential incorporation of remote sensing techniques at a field scale for identifying and evaluating plant stress both spatially and temporally.

Over 6,000 million individuals globally are reliant on agriculture for the production of foodstuffs. In the next 40 years the global population is projected to be 50% larger than it is today (Tillman et al., 2002). While yields of many crops have increased in the last century, future growth is uncertain. Much of the world’s high quality arable land is already in production (Tillman et al., 2002). Production agriculture will increasingly be forced to expand into more marginal land. The commercial production of crops also has environmental impacts. Managing potential pollutants such as and pesticides will become increasingly important. Corn (*Zea mays* L.) is a major U.S. commodity with over 28 million hectares planted annually since 1989 (United States Department of Agriculture, 2011). In 2010, approximately 5 billion kg of nitrogen were applied to American corn fields and nearly 2 billion kg of both phosphorous and potassium fertilizers (United States Department of Agriculture, 2011A). Additionally, of land in corn production, 66% was treated with glyphosate isopropylamine salt to control weeds, more than 25 million kg of one singularly applied chemical (United States Department of Agriculture, 2011B). In 2008, approximately 22 million hectares of American farmland was irrigated (United Sates Department of Agriculture, 2008). The challenge of meeting global demand, while managing our natural resources, will require producers to focus on mitigating crop stress. An understanding of the physiochemical impacts of plant stress and their spectral responses, through the use of remote sensing, can allow producers to make decisions that are agronomically sound environmentally friendly, and economically feasible.

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CHAPTER II: REVIEW OF THE LITERATURE

Remote Sensing

Remote sensing, or attaining information about an object or area without making direct contact, often utilizes ground-based sensors, satellites or aerial imagery (Printer et al., 2003; Hatfield et al., 2008). The use of remote sensing tools for agricultural purposes is not a conventional practice, although its application is not new. The use of spectral measurements in the life sciences to gain a better understanding of plant growth and development is well documented. Research done in the mid to latter part of the twentieth century has led to a better understanding of the spectral properties of plants (Moss et al., 1952; Gates et al., 1964; Gausman et al., 1973).

Spectral Properties of Plants

Total solar radiation absorbed by a leaf is directly related to the amount of photosynthetic pigment present (Gates et al., 1964). Chlorophyll, both Chl a and b, contained in the chloroplast constitutes much of this photosynthetic pigment. Camp et al. (1982) evaluated the changes in photosynthetic enzymes and photochemical activities in vegetative wheat (*Triticum aestivum* L.) leaves during senescence. Their study showed that as a wheat leaf senesced, there was a loss of photosynthetic activity. It was discovered that this reduction in photosynthesis was attributable to a loss in total number of chloroplasts.

Identification of appropriate wavelengths for monitoring changes in chlorophyll content has focused on studying the absorption coefficient, ratio of light energy absorbed to incident light, of chlorophyll. The absorption coefficient describes the Incident light in the green (~550 nm) and red edge (~700 nm) spectra has been found to have a very low absorption coefficient as compared to light in the blue (~450 nm) and red (~650 nm) spectra. However, the depth of light penetration into the leaf has been shown to be greater in the green and red edge spectra than that of the blue and red. Research has also found greater than 80% of incident light in the regions of 400 to 700 nm is absorbed (Moss et al., 1952). As a result, light in the green and red edge spectra has been shown to be more sensitive to changes in chlorophyll content than other wavelengths as its absorption coefficient was adequate but not high enough to easily saturate. This methodology was outlined in a study by Gitelson et al. (2003) demonstrating the relationship between leaf chlorophyll content and spectral reflectance.

In addition to studying the spectral properties at the molecular level Gates et al. (1964) studied several species. The authors determined that as leaves were sampled from a lighter to darker color the amount of absorbance in the visible spectrum increased. It was determined that maximum absorbance occurred at 680 nm and a minimum was established at 550 nm. It was also established that not only does the intensity of incident light have an impact on the amount of solar radiation absorbed, but also the angle that light strikes the plant surface.

Vegetative Indices

An understanding of the spectral properties of plants presented the opportunity to analyze plants, and more importantly plant populations non-destructively by interpreting the amount of incident light absorbed and reflected at specific wavelengths. A common means of making this analysis is by comparing the amount of red light and near infrared light beneath a plant canopy to that above the canopy. An increasing amount of vegetation, or active photosynthetic tissue, will increase the amount of light absorbed in the red spectrum and light reflected in the near-infrared (Federer et al., 1966). This concept was implemented in the evaluation of forest canopies and the development of indirect measurements of leaf area index (LAI). Leaf area index is defined as total photosynthetic tissue per unit ground surface. A direct measurement of LAI involves periodically destructively sampling an area and is highly dependent on sampling conditions (Gower et al., 1999). Jordan, (1969) demonstrated that by using a light ratio method of incident light of 675/800 nm beneath a forest canopy as compared to above, LAI could be determined indirectly. The authors also concluded that while LAI could be estimated remotely, environmental conditions (cloud cover, angle of incident sunlight, etc.) greatly impacted the accuracy of indirect measurements.

The same principals have been implemented in evaluating grass canopies. With increasing green biomass, incident light in the red spectra (630-690 nm) is increasingly absorbed. This increased absorbance of red radiance is inversely proportional to the chlorophyll content of vegetative cover. Irradiance in the near infrared spectrum is defined by a lack of absorption and is reflected by photosynthetically active tissue. Research concluded on various ratios has shown that analysis using wavelengths from the red and near infrared spectrum are sensitive to green leaf material (Tucker, 1979).

The concept of evaluating the amount of incident light absorbed and reflected at different wavelengths has been utilized in the development of several ratios, collectively known as vegetative indices, which are sensitive to different environmental and physiological parameters. Frequently used indices have been outlined by Hatfield et al. (2008). Application of common indices include: chlorophyll indices ($Cl_{green} = (R_{NIR}/R_{green})-1$) for estimating chlorophyll content

(Gitelson et al., 2005), and the soil adjusted vegetation index (SAVI = (R_{NIR}-R_{red})(I+L)/(R_{NIR}+R_{red}+L)) for LAI estimation (Huete, 1988).

The normalized difference vegetative index (NDVI) is a widely used vegetative index. Developed and implemented in the late 1970's (Deering, 1978) NDVI has gained a wide acceptance primarily due to its ease of use, utilizing only two wavelengths, and the important plant characteristics the ratio reflects. NDVI has been related to nitrogen status, chlorophyll content, green leaf biomass, and grain yield (Shanahan et al., 2003; Ma et al., 1996; Solari et al., 2008; Shanahan et al., 2001). Since that time variations of the index have been established using different specific wavelengths (e.g. GNDVI, drawing from the green spectrum for visible light), however, the basic index remains unchanged. NDVI is calculated as:

$$NDVI = (R_{NIR}-R_{VIS})/(R_{NIR}+R_{VIS})$$

Where R_{NIR} represents light reflected in the near infrared spectra and R_{VIS} in the visible. Applying the concept of normalization, the comparison of absorbed incident light to reflected can be placed in a simple ratio that exists on a scale varying between -1.0 and 1.0 making evaluation of environmental responses comparable (Crippen, 1990). The development of active sensors has made sampling relatively insensitive to changes in ambient light and environmental constraints. Active sensors contain modulated light emitting diodes that emit light at specific wavelengths on a canopy. A sensor measures the amount of light reflected rather than being reliant on ambient sunlight (Shaver et al., 2010).

Plant Stress

Environmental Interaction

The impact of environmental stress on the physiological processes of a plant defines a crop's overall productivity. Boyer (1982) described the effects environmental stress has on modern crop production. Unfavorable environmental conditions can reduce yields by more than 70%. Modern breeding programs have created hybrids with increased genetic potential than older corn varieties. Breeders have selected varieties able to tolerate greater plant densities and environmental stresses (Meghji et al., 1983; Tollenaar, 1989). However, genetic improvements can only account for about half the yield increase realized in the modern breeding era (Boyer, 1982). Additional gains are a result of improved management of environmental stress. Reducing environmental stress can be associated with irrigation, increased fertility, and pest management.

Fulton (1970) described the relationship between soil moisture and corn yields, concluding that once available soil moisture levels at 40 cm dropped below 25% (moisture tension in excess of 5 bars) corn yield was severely impeded. In several instances, application of irrigation water doubled yield. This was particularly evident with late season moisture stress. Drought stress during flowering can cause a delay in silking, disrupting anthesis; resulting in barren ears (Herrero et al., 1980). Decreased photosynthesis is a contributing factor to yield reduction due to moisture stress. Drought stress in the two weeks following silking can reduce the crop growth rate by 20% (Dwyer et al., 1992). A reduction in stem elongation, cob length, leaf area, assimilation, and grain yield can be expected as a result of moisture stress (Denmead et al., 1960).

High temperatures can also induce yield reducing stress in corn. Temperatures exceeding 37.5° C inhibit photosynthesis and as temperature increases to 45° C, the rate of photosynthesis may be inhibited by as much as 95% (Crafts-Brandner et al., 2002). The result of heat stress in corn can result in detrimental effects on the development of tassel initiation, time of flowering, anthesis, and kernel development.

High plant densities can stress developing corn plants. Jacobs et al. (1991) demonstrated that with increased population, plant productivity was decreased in total grain bearing ears, number of kernels, and kernel dry weight. Total grain yield per unit area increased with greater populations due to the number of total ears, regardless of individual plant production. However, when restrictions were put on available nitrogen, a 65% reduction in yield was observed. High populations also delay silking, causing potential problems during anthesis under environmentally stressful conditions (Jacobs et al., 1991).

Adequate fertility can impact the amount of stress induced on a developing corn plant. Nitrogen availability is an important contributing factor to proper growth and development. Nitrogen is utilized in the production of nucleic acids and proteins. Chlorophyll production is also dependent on the availability of nitrogen. Multiple studies have been done describing the reduction in growth and productivity associated with inadequate levels of nitrogen fertilization (eg. Eck, 1984; Jacobs et al., 1991). Availability of nitrogen is involved in the determination of kernel number. In order to obtain maximal yield of corn more than 200 kg N/ha may be required (Eck, 1984).

Environmental stresses can have a direct impact on the photosynthetic productivity of a plant or crop canopy. Increasing the ambient air temperature in wheat (*Triticum aestivum* L.)

production from moderate (22/17°C) to high (32/27°C) can decrease the photosynthetic rate of maturing plants by 11% while reducing total biomass production by 32% (Al-Khatib et al., 1990). Moisture stress can reduce net photosynthesis in corn by 25% when leaf water potentials reach -16 bars (Boyer, 1970). In cotton, increased photosynthetic rate was consistently associated with higher rates of nitrogen application and consequently higher yields (Bondada et al., 1996).

Modern crop production has put an emphasis on managing inputs while mitigating the risks associated with environmental stress. Variations in local environments and at the plant scale make managing crop growth and development across a field a difficult task. A precise nondestructive evaluation of crop stress is required in order to prioritize management decisions. Current research indicates that the alleviation of stress will increase productivity (Boyer, 1982). The acquisition of this information involved the collective efforts of research scientists, years of study, and destructive measurements. The application and implementation of these concepts on a production scale will require the characterization of multiple different environments. A simplistic, cost effective, and timely non-destructive method for analyzing changes in photosynthetic capacity is required by industry specialists in order to build a collective knowledge.

Spectral Response

Environmental stresses also elicit a change in the spectral properties of leaves. Carter, (1993) evaluated leaf spectral responses of multiple species to imposed stresses: plant competition, disease interaction, insufficient ectomycorrhizal infection, senescence, herbicide damage, increased ozone, dehydration, and saline soils. The common response across all treatments was increased reflectance in the green (491-575 nm) and red (647-760 nm) wavelengths. Reflectance in the infrared spectrum remained unchanged across treatments. The researchers also observed a shift in the absorption curve toward shorter wavelengths in response to stresses. The rationale for this response was that stress induced reductions in chlorophyll. Chl *a* has relatively low absorbency in the green and red spectrums. Even small changes in chlorophyll concentration can cause increased reflection at these wavelengths.

Further evidence of stress-induced spectral reflectance responses have been replicated *in vitro*. Carter et al. (2001) measured the reflectance of incident light in the presence of two stresses: insect infection of loblolly pine (*Pinus taeda* L.) and nitrogen deficiency in radiate pine (*P. radiate* D. Don). The results were consistent with previous research; increased reflectance in the 400-850 nm range from induced stress. The increase in reflectance was greatest in the nitrogen deficient treatment, peaking at 566 and 702 nm. These findings were compared to reflectance data from *in vitro* leaf models of differing chlorophyll concentration. It was shown that stress induced spectral changes were similar to those found by decreasing chlorophyll concentration in leaf models. These findings were generally consistent across species and stresses.

These physiological effects have been reported in corn as well. Zhao et al. (2003) induced differing levels of nitrogen stress on corn and measured growth parameters, chlorophyll concentration, photosynthetic rates, and reflectance. The study demonstrated that reductions in leaf nitrogen concentrations are greater in plants suffering from inadequate soil nitrogen availability. Reduced nitrogen concentrations were correlated with lower rates of stem elongation and leaf area. Additionally, 42 days after emergence, there was a more than a 60% reduction in Chl *a*, eliciting increased reflectance near 550 and 710 nm. These results were consistent with previous studies both in corn and other species on the response of chlorophyll to nitrogen deprivation.

Micronutrient deficiencies can also cause stress resulting in a spectral response similar to those described previously for nitrogen. Masoni et al. (1996) evaluated corn plants with iron, sulfur, magnesium, and manganese deficiencies individually. Leaf chlorophyll concentrations decreased as leaf micronutrient concentrations decreased. Chl *a* concentrations were 22% of the unstressed control when iron, magnesium or manganese were limiting. Sulfur deficiencies caused a 50% reduction in Chl *a* concentrations. As demonstrated in previous studies, reduced chlorophyll concentrations as a result of stress resulted in decreased light absorbency and increased reflectance near 555 and 700 nm.

<u>Non-Destructive Evaluation of Plant Growth and Development</u>

Chlorophyll Content

Chlorophyll content in a plant is directly related to photosynthetic potential (Hatfield et al., 2008). In higher plants, total chlorophyll content will change in response to stages of development or plant stress. Monitoring chlorophyll content can give an instantaneous comparative tool for evaluating the current physiological state of a plant. This methodology was outlined in a study by Gitelson et al. (1997) investigating the validity of vegetative indices for assessing chlorophyll content. The authors tested multiple species, and determined that reflectance and absorption variance to incident light at 530-630 nm and near 700 nm were highly sensitive to changes in chlorophyll content from 0.3 to greater than 60μg cm^{-2}. Reflectance at the specific wavelengths of 700 and 550 nm correlated with chlorophyll content ($r^2 > 0.97$).

Using a wavelength from the near infrared spectrum (750-900nm) as a relatively insensitive term, an index was established for predictive measurements (R750/R550). It was demonstrated that predicted chlorophyll content was correlated with analytically measured chlorophyll content at (r^2 = .94). The researchers concluded that the indices tested were sensitive to changes in chlorophyll content for an individual leaf sample.

Ciganda et al. (2009) conducted a similar study on corn, sampling individual leaves biweekly in order to characterize canopy chlorophyll. The red edge chlorophyll index ($Cl_{red\ edge}=(R_{NIR}/R_{red\ edge})-1$) was used to remotely estimate total chlorophyll content. The authors were able to establish a linear best-fit line ($r^2 > 0.94$) demonstrating the relationship between analytically sampled chlorophyll content and the reflectance-based estimate.

Many studies involving non-destructive estimation of chlorophyll content have been limited by their reliance on ground truthing with destructive analysis. Also, poor application to a larger scale due to restrictions associated with sampling and/or a particular vegetative index has limited adoption. Shanahan et al. (2003) proposed a study evaluating the use of two indices (NDVI and GNDVI) on a large plot scale. The experiment was conducted on four varieties of irrigated corn treated with five differing levels of nitrogen. Remote measurements were taken with active sensors emitting light in four bands: blue (460 nm), green (555 nm), red (680 nm), and NIR (800 nm). The authors concluded that differences in NDVI was significantly impacted by nitrogen and sampling date. Also, increased nitrogen was correlated to increased chlorophyll content. However, strong correlation with chlorophyll content was not achieved on a large scale.

Nutrient Status

Adequate fertility positively affects corn growth, warranting the use of inorganic fertilizers (Belay et al., 2002). Understanding the relationship between adequate fertilization and overall productivity of plants, specifically plants of economic importance, has led many researchers to explore the possibilities of using remote sensing techniques to evaluate the nutritional status of plants (eg. Ma et al., 1996; Solari et al., 2008; Mistele et al., 2008). Much of the focus has been on detecting physiological differences associated with variance in nitrogen availability. Chlorophyll content and leaf nitrogen concentrations have been correlated throughout the growing season (Wolfe et al., 1988). Nitrogen deficiency has a direct impact on the photosynthetic rate of leaves. Productivity of corn has been shown to be reduced when nitrogen availability is limited, resulting in lower kernel dry weight (Gentry et al., 1993). Recognizing the relationship between chlorophyll and reflectance measurements makes remote evaluation of nitrogen status a logical choice.

Choosing the appropriate wavelengths for investigation when considering growth related to plant nitrogen concentration is critical. It has been demonstrated that nitrogen concentration and availability affect chlorophyll content and productivity (Belay et al., 2002; Gentry et al., 1993; Wolfe et al., 1988). Measuring chlorophyll response to reflectance acts simply as a proxy for variations in nitrogen concentration. Hansen et al. (2003) concluded that NDVI was a useful tool in evaluating small grain growth and development. The authors noted that using different wavelengths to calculate the vegetative index changed the coefficients of determination for different levels of green biomass, leaf area, chlorophyll density, and nitrogen concentration. A singular set of wavelengths could not be determined to best fit all crop variables.

An accurate approach for estimating nitrogen uptake has been the identification of the red edge inflection point (REIP). The REIP has been shown to have a curvilinear response to nitrogen uptake (r^2 = .90) in wheat (Mistele et al., 2008). Similar results have been demonstrated in other crops such as corn. Schlemmer et al. (2005) established that the red edge inflection point shifts towards higher wavelengths (730 nm) at higher nitrogen rates as a function of a plant's nitrogen status. While the accuracy of this index has been shown, it has gained little acceptance on a practical scale due to its limitations. The calculation of the REIP requires the measurement of four wavelengths: 670, 780, 700, and 740 nm. Sensors exist with this capability, however, most are passive. As discussed earlier, passive sensors are impacted greatly by shifts in environmental conditions, requiring constant calibration.

Blackmer et al. (1994) established a relationship between light reflectance readings at 550 nm and leaf nitrogen in corn. The investigators demonstrated in laboratory studies under varying rates of nitrogen that a positive correlation existed between leaf nitrogen, chlorophyll meter readings, and grain yield with a similar coefficient of determination. Initial research provided the basis for more extensive studies exploring the potential of vegetative indices as a predictive tool for nitrogen content.

The relationship between applied nitrogen, light reflectance, and NDVI in corn was explored by Ma et al. (1996). Large differences in leaf area, chlorophyll meter readings, field greenness and light reflectance were noted in response to varying rates of applied nitrogen. Additionally, varietal differences in light reflectance were noted following anthesis. It was concluded that higher NDVI values were associated with higher nitrogen rates. The conclusions derived from this study provided a basis for using NDVI to evaluate the nitrogen status of corn.

Solari et al. (2008) investigated the potential use of active sensors at a field scale in determining nitrogen status in corn. Irrigated plots with uniform soils and fertilization, excluding nitrogen, were established in 2005. Differing rates of nitrogen and time of application were administered in order to induce variable growth patterns. They evaluated the efficacy of two vegetative indices, NDVI590 and CI590. The authors were able to conclude that both indices were sensitive to differences in nitrogen, hybrid, and growth stage. Sensor readings were also found to be more associated with chlorophyll content during vegetative growth stages than during reproductive stages.

Recently, variable rate nitrogen application has gained notoriety based on the emergence of two widely adopted NDVI sensors. There has been increased demand for an understanding of how NDVI can be utilized in nitrogen management. Several studies have been conducted evaluating the efficacy of the GreenSeeker Model 505 (NTech Industries Inc.), and Crop Circle ACS-210 (Holland Scientific, Inc.) in measuring nitrogen variability of corn. The difference between sensors are the wavelengths used to calculate NDVI. While both use wavelengths in the visible and near infrared spectrums, the GreenSeeker Model 505 utilizes reflectance measurements from 660 nm and 770 nm while the Crop Circle ACS-210 measures reflectance at 590 nm and 880 nm. Under varying rates of fertilization both sensors are sensitive to applied nitrogen ($r^2 > 0.89$). However, at later growth stages the GreenSeeker Model 550 saturates much sooner than the Crop Circle ACS-210 making it less sensitive to changes in vegetative growth (Shaver et al., 2011). Additionally, when tested under field conditions, the GreenSeeker was sensitive to row spacing and sensor movement speed. Conversely, the Crop Circle ACS-210 is stable over early and late growth stages as well as across multiple row spacing’s and sensor movement speeds (Shaver et al., 2010). In choosing an appropriate sensor for evaluating a variable environment across the entire growing season the Crop Circle ACS-210 provides a more reliable estimation of canopy development (Shaver et al., 2010; Shaver et al., 2011).

Yield Estimation

Attempts at using active sensors to predict grain yield in-season have been explored intensively but the research has been inconclusive. While a relationship has been established between vegetative indices, such as NDVI, and current levels of green leaf biomass (Gitelson et al., 2003), extrapolating this data as a predictive means for yield estimation has proven more difficult.

In wheat, attempts have been made to identify a specific growth stage in which remotely sensed data is most correlated with final grain yield. In evaluating NDVI, Feekes growth stage 5 has been shown to be more correlated with grain yield then other stages of development (Moges et al., 2004). The establishment of a critical stage of sampling demonstrates an important balance between the absolute value of an index, and its sensitivity to slight changes in development. Raun et al. (2001) demonstrated the ability of NDVI to predict final grain yield in winter wheat at 9 locations over a 2 year study. Estimated grain yields were able to describe 83% of the variability, however, values often over or under estimated final grain yield significantly.

Several studies done under restricted management situations such as irrigation and limited soil variability have demonstrated the relationship of NDVI and other vegetative indices with final grain yield in corn. Mean NDVI values generally peak at tassel, however, values during the mid-grain fill period were found to be the most correlated to final grain yield. This period displays the greatest potential for estimating yield (Shanahan et al., 2001). The calculated in-season estimated yield (INSEY), based on NDVI measurements and accumulated growing degree days, has shown to have a linear relationship with actual yield. The strength of this relationship has proven to be variable over space and time (Inman et al., 2007). Contributing factors to inconsistencies with estimating yield have been sampling date, hybrid variation, seasonal changes, spatial differences, and nitrogen fertilization (Shanahan et al., 2001; Inman et al., 2007).

Spatial Variability

Landscape Position

Implementing the discussed techniques for monitoring crop growth and development in commercially based production systems faces unique challenges. Commercial corn fields can be characterized by differences in production history, changes in soils, elevation gradients affecting the movement of water and nutrients, and a host of other environmental shifts imposing spatial variability. These spatial discrepancies can cause changes in localized levels of plant stress and ultimately variations in plant productivity across a landscape.

Changes in slope can have the greatest impact on grain yield variability (Jiang et al., 2004; Kravchenko et al., 2005; Kravchenko et al., 2000). Corn yield is lowest at the summit of a sloping landscape and highest at low lying landscape positions. Topology and related soil factors such as depth and drainage have a large impact on corn grain yield (Timlin et al., 1998). Commercial corn production frequently has higher fertility levels at lower elevations. This is primarily due to water flow and erosion depositing organic matter at lower elevations or in depression areas. The effect of organic matter accumulation is greater on soils formed from parent material naturally low in organic matter (Jiang et al., 2004; Kravchenko et al., 2000). In addition, phosphorous and potassium concentrations tend to be higher at lower elevations based on the same principles, although, macronutrient deposition hasn't proven to be as correlated with slope as organic matter (Kravchenko et al., 2000). Topological and associated soil information is an important tool in explaining spatial variations in grain yield. The combined information of a location's topography and slope explain 30-85% of the yield variability in corn and soybean (*Glycine max* L.) cropping systems (Jiang et al., 2004).

Understanding topography and soil related properties provides a significant understanding of grain yield variation, however, it can only describe a portion of the inconsistencies in crop production. Stressful conditions, regardless of source, result in significant increases in growth and production variability. Landscape effects are often substantially impacted by seasonal weather conditions. The inherent differences in landscape position become exacerbated during dry years. Areas with greater organic matter and water holding capacity are less affected by droughty conditions then upland areas that have been severely degraded (Kravchenko et al., 2005; Timlin et al., 1998). Conversely, greater than average rainfall can cause similar effects in depression areas where ponding can occur (Ginting et al., 2003). Most studies contend that adequate to above average seasonal rainfall reduces in-field variability of crop growth and grain yield.

Tillage and management practices across a landscape can also impact plant growth and productivity. Lower input systems such as reduced tillage and/or reduced chemical dependence increase spatial variability. This has been attributed to stresses imposed by nutrient availability in the rooting zone for high input crops such as corn and early season soil conditions (Kravchenko et al., 2005; Ginting et al., 2003). Dry seasons favor a greater percent residue cover, achieved by implementing conservation tillage practices, due to the benefits derived from water conservation. However, wet conditions favor conventional tillage and a relatively drier seed bed as opposed to reduced tillage (Ginting et al., 2003).

Spatial variability in crop productivity is only evident when differences in resources become limiting. Soil qualities related to agronomic management can greatly influence the availability of resources. No-till production with residue removal can increase spatial variability as it relates to crop performance resulting in lower soil moisture, pH, organic matter, and soil structure (Verhulst et al., 2008). Lower organic matter and decreased soil moisture due to structural degradation result in stressful conditions exacerbating any spatial differences within an area. This is visible throughout the growing season as not only is final yield influenced but emerging plants are stunted in a no-till residue removal scenario as opposed to a higher input system (Govaers et al., 2007).

Topographic and spatial distribution of soil properties are a large determinant of spatial variability in grain yield. This spatial variability is directly impacted by temporal changes. Temporal changes can be both natural, as with weather, and managerial, as with tillage. While generalities can be made about a production system, and within specific crop production years, an in-season method for evaluating crop status across a landscape is needed.

Remote Estimations of Spatial Variance in Crop Performance

Scientists have investigated the response of remotely sensed information to changes in management practices and/or inherent environmental conditions. While these have provided a basis for further investigation, many are conducted under rigid constraints, i.e. irrigation and/or minor shifts in soils etc. This makes extrapolation to a larger field scale difficult.

Addressing the potential impact of production variation on vegetative indices, Hatfield et al. (2010) conducted research on four crops: corn, soybean, wheat, and canola (*Brassica napus* L.). The study was conducted in central Iowa on fine-loamy soils. Each species was subjected to different management treatments including tillage, nitrogen fertilization, and varietal differences. Spectral observations were taken over the course of the entire growing season using two ground based sensors. The authors showed a consistent continuum of NDVI values between treatments from 0.15 at bare soil to 0.9 once canopy closure was achieved. They demonstrated that as a crop approached an LAI of 4 NDVI becomes saturated and less sensitive to changes in vegetative development. The authors concluded after calculating multiple vegetative indices temporally, six indices were useful in evaluating different crop phenology and management practices. On a large plot scale, mean values of chlorophyll index were shown to be related to varietal and tillage differences in the mid-vegetative stage, reproductive onset, and mid-grain fill in corn (Zea mays L.). There proved to be no difference of year in any treatment, proving vegetative indices are a stable evaluation tool of crops over time. Additionally, reflectance in the NIR wavelength increased with vegetative growth across all species.

Under the assumption that spatial differences in crop productivity only manifest when resources limit crop performance. Verhulst et al., (2008) demonstrated that the intrinsic spatial soil characteristics could be associated to crop performance, and that remote sensing technology could be used to identify areas of low productivity. The authors consistently demonstrated that plots of corn managed as no-till with residue removal had significantly lower mean and minimum NDVI values. This was supported by their agronomic research discussed earlier describing the soil degradation that occurs under low-input management practices. They also showed a greater standard deviation and CV of NDVI values in low-input management systems which were reflected in the greater spatial variability of crop production. Using NDVI values acquired throughout the growing season, the researchers were able to develop a predictive model for biomass and grain yield.

The development of management zones based on inherent characteristics of a location as well as remotely sensed crop performance indicators has been a goal of many. Characterizing a site has proven to be an arduous process, however, under irrigated conditions a relationship between spatial information of soil and plant data can provide a basis for the establishment of management zones (Lopez-Lozano et al., 2010). This opens an avenue for in-season descriptive analysis of production variables. Determining the critical growth stage to sample, the appropriate spectrum for crop performance analysis, and how implementation on farm machinery impacts the efficacy of sensing equipment are questions that deserve more exploration. More study is required over a variable landscape incorporating many of the discussed issues under dry-land conditions in order to determine the appropriateness of this theory for widespread adoption.

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CHAPTER III: NORMALIZED DIFFERENCE VEGETATIVE INDEX (NDVI) USED TO IDENTIFY SPATIAL VARIABILITY IN VEGETATIVE GROWTH AND GRAIN YIELD OF CORN (*ZEA MAYS* L.)

ABSTRACT. Understanding plant stress and its spatial distribution has been a goal of both crop physiologists and producers. Recognizing variability in plant growth early can aid in identifying yield-limiting factors such as soils, nutrient availability, and/or environmental limitations. Active sensors have been used to gather reflectance data from crop canopies and to calculate NDVI (Normalized Difference Vegetative Index). NDVI has been associated with percent ground cover, LAI, biomass accumulation, and nitrogen use efficiency. This study contends that NDVI can be used to characterize spatial variability in plant growth and is correlated with grain yield. NDVI values were measured bi-weekly through the growing seasons of 2010 and 2011in corn (*Zea mays* L.) grown at a location with soil and topographic variability. Grain yield was collected following each growing season. Management practices and characteristics of the site were associated with each plot in order to identify contributing factors to spatial variations in NDVI values. Two cropping rotations were used, continuous corn, and a corn soybean small grain/soybean double crop. Results showed differences in corn growth at different landscape positions could be identified with NDVI. The strength of this relationship was greatest eight weeks after planting. A relationship was also established between NDVI and grain yield. NDVI measurements can be used to identify the variability of grain yield in continuous corn production when taken following the accumulation of 800 to 900 growing degree days. This demonstrated success presents the opportunity to use this technology in characterizing production potential and making managerial decisions across a landscape.

Introduction

A precise evaluation of plant stress in corn (*Zea mays* L.) production is required in order to prioritize management decisions and to facilitate high throughput screening of breeding materials. Corn is a major U.S. commodity with over 28 million hectares planted annually since 1989 (United States Department of Agriculture, 2011). Scientific and technological advancements in agriculture have enabled the deployment of new tools for describing large areas of crop production to facilitate management and marketing decisions. Global positioning systems, remote sensing techniques, and yield mapping software make it possible to associate both spatial and temporal information on a broad scale (Arslan et al., 2002; Pinter et al., 2003; Hatfield et al., 2008). Data mining to acquire soil fertility, pest management, yield, and seasonal crop performance information have become a major focus (Robert, 2002). Understanding spatial variation of indirect measurements can have a great effect on crop production management decisions for researchers and producers.

Environmental stress during the growing season can have a significant effect on corn growth. Drought conditions can reduce grain yield. The quantitative impact of dry conditions on grain yield varies depending on the timing of stress and duration (Fulton, 1970; Herrero et al., 1980; Dwyer et al., 1992). Likewise, high temperatures can influence crop growth and development decreasing the photosynthetic rate when heat becomes excessive (Crafts-Brandner et al., 2002). Fertility limitations have been identified as a major restraint in achieving maximum yield. Nitrogen availability throughout the vegetative development of corn becomes critical in the later vegetative stages for grain formation (Eck, 1984; Jacobs et al., 1991). Modern crop production emphasizes managing inputs and mitigating the risks associated with environmental stress.

A common approach to monitoring plant growth and development non-destructively has been to compare the amount of red and near infrared irradiance reflected from the crop canopy. An increasing amount of vegetation, or active photosynthetic tissue, will increase the amount of irradiance absorbed in the red spectrum and irradiance reflected in the near-infrared (Federer et al., 1966). The amount of incident light absorbed and reflected in different wavelengths has been utilized to develop several ratios, collectively known as vegetative indices, that are sensitive to different environmental and physiological parameters (Hatfield et al., 2008).

The normalized difference vegetative index (NDVI) is an important ratio and has been widely used. Developed in the late 1970's (Deering, 1978), NDVI has gained wide acceptance due to its ease of use and important plant characteristics it reflects. NDVI has been related to nitrogen status, chlorophyll content, green leaf biomass, and grain yield (Shanahan et al., 2003; Ma et al., 1996; Solari et al., 2008; Shanahan et al., 2001). Since its development variations have been established using different specific wavelengths (GNDVI, drawing from the green spectrum for visible irradiance), however, the basic ratio remains unchanged. NDVI is calculated as:

$$NDVI = (R_{NIR}-R_{VIS}) / (R_{NIR}+R_{VIS})$$

R_{NIR} represents irradiance reflectance in the near infrared spectrum and R_{VIS} in the visible. Applying the concept of normalization, the comparison of absorbed incident light to reflected can be placed in a simple ratio on a scale varying between -1.0 and 1.0 making evaluation of environmental responses comparable (Crippen, 1990). Active sensors contain modulated light emitting diodes that emit light at specific wavelengths on a canopy. Rather than being reliant on ambient sunlight, active sensors measure the amount of emitted light reflected (Shaver et al., 2010).

NDVI values can be impacted by any factor causing a reduction in plant growth. Commercial corn fields have different production histories, soils, elevation gradients, and other environmental shifts imposing spatial variability on crop growth. These spatial variations can cause changes in localized levels of plant stress and variations in plant productivity across a landscape. Users of NDVI must be aware of limiting factors imparting stress on a production area.

Topography and related soil factors such as depth and drainage can affect corn grain yield (Timlin et al., 1998). Additionally, increasing slope increases organic matter deposition and nutrient accumulation at lower landscape positions due to water flow (Kravchenko et al., 2000; Jiang et al., 2004). Corn grain yield tends to be lowest at the summit of a sloping landscape and highest at low lying landscape positions. Seasonal weather conditions impact plant growth. Inherent differences in landscape position become intensified during dry years. Areas with greater organic matter and water holding capacity are less affected by droughty conditions than upland areas that have been severely degraded (Kravchenko et al., 2005; Timlin et al., 1998). Spatial variability in crop productivity is often only evident when differences in resources become limiting.

Recent studies have explored the ability of NDVI to evaluate changes in management practices and environmental conditions. NDVI has proven useful in evaluating fertility programs, management practices such as tillage, and crop phenology (Verhulst et al., 2008; Hatfield et al., 2010). A relationship between spatial information of soil and plant characteristics can provide a basis for the establishment of management zones under irrigated conditions (Lopez-Lozano et al., 2010), however, this type of categorization has proven to be an arduous task for most producers managing dry-land fields.

The objective of this study was to determine if NDVI can be used as a nondestructive method to differentiate corn growth in-season across a landscape under dry-land conditions. Additionally, focus was placed on discovering the critical point of the growing season at which NDVI generates the greatest relative difference between landscape positions. Also, determining the appropriate time for collecting NDVI measurements when trying to identify areas of high and low productivity as it relates to grain yield was explored.

Materials and Methods

Field experiments were conducted in 2010 and 2011 at a satellite research location (41° 55' 44" N, 93° 45' 59" W) of Iowa State University near Madrid, IA, which was established in 2009. The chosen site had variable soils and elevation. The research site was located on a hillside with an elevation difference of 20.18 m from summit to base on an area of approximately 25 ha. The hillside had been terraced before establishment of the research site. The area of interest included soils in order of relative quantity: Clarion, Coland, Nicollet, Zenor, and Spillville. Prior to field experiments, the site was managed as a production row-crop operation in corn (*Zea mays* L.)-soybean (*Glycine max* L.) rotation. Several rotational treatments were established in 2009 for a multifaceted study. Plots measured 20 × 20 m and were placed in a randomized replicated block design. Each rotation included three replications and was placed across five landscape positions: summit, shoulderslope, backslope, toeslope, and floodplain. Prior to site establishment two parallel terraces were constructed across the landscape. The backslope was the only landscape position located between the two terraces. All treatments were managed as no-tillage with stover removal from the previous cropping sequence. The 2011 cropping season had less rainfall than 2010, with approximately 50 cm less precipitation from the beginning of April through the end of September.

In 2010 all collected measurements were from plots managed under a continuous corn rotation. The 2011 cropping season included an additional set of data from the continuous corn plots. Corn grown in rotation with triticale (× *Triticosecale*) and soybean was also sampled. Rates of fertilization prior to planting included: 170 kg ha^{-1} N (urea), 91 kg ha^{-1} K (potash), and 24 kg ha^{-1} P (triple super phosphate) annually. Nitrogen fertilization was reduced by 34 kg ha^{-1} on corn grown in rotation with triticale and soybeans in 2011. One full-season hybrid, Pioneer 33W84 (111 day relative maturity), was used for all treatments and both years. The chosen hybrid was common to Central Iowa. Landscape positions and treatments were planted on 7 May 2010 and 10 May 2011 at a rate of 79,000 seeds ha^{-1} using a no-till planter at 76-cm spacing. Glyphosate herbicide was applied in early June to control weed populations.

NDVI measurements were collected from the canopy at six intervals: 3, 4, 6, 8, 10, and 12 weeks after planting during 2010 and 2011. Each measurement was associated with the total accumulated growing degree days for the respective year. Measurements were taken using a Crop Circle™ ACS-210 (Holland Scientific, Lincoln, NE) active sensor which emits irradiance and measures reflectance at 590 nm in the visible spectrum and 880 nm in the near-infrared. The active sensor was mounted on an all-terrain vehicle for early season sampling until plant growth restricted movement through plots. Late season measurements were accomplished by mounting the active sensor to a mast and walking the sampling area. A constant distance of approximately 90 cm was maintained between the uppermost leaf of the crop canopy and the active sensor. Each plot value for NDVI was comprised of 200-300 subsamples, with the resulting mean expressed as a single unit. Subsamples were taken by making three randomly assigned passes across each plot at a constant speed, measuring NDVI over the inter-row space at a frequency of 5 Hz. Each subsample was georeferenced using a mounted global positioning system. Grain yield was determined for each plot. Grain yield samples were made from two representative subsamples. Ears from two randomly assigned 10 m lengths per plot were hand harvested. Collected ears were dried, shelled, and weighed (cob and grain individually). Reported yield was standardized to 15.5% kernel moisture.

The GLM procedure of SAS (SAS Institute Inc., 2002) was used to conduct the analysis of variance and was performed separately for grain yield, and sampling period of NDVI. Mean comparisons between landscape positions using Fisher's least significant difference test ($P \leq 0.10$) were done at each sampling period. Pearson correlation coefficients were determined between landscape position, grain yield, and NDVI measurements 3, 4, 6, 8, 10, and 12 weeks after planting.

Results

Differences in NDVI were not affected by landscape position at any sampling period in 2010. However, mean comparisons showed differences in NDVI by landscape position at different sampling dates (Table 1). Differences in NDVI during the 2011 cropping season were affected by landscape position 6, 8, and 10 weeks after planting. Mean comparisons of landscape positions identified differences in NDVI during each sampling period in 2011 (Table 1). Landscape position and NDVI were correlated over both rotational treatments and years (Table 2).

Differences in NDVI values between landscape positions were not observed in 2010 until eight weeks after planting (Table 1). This was supported by the absence of a correlation between landscape position and NDVI until eight weeks after planting (Table 2). The relationship identified at week eight ($P \leq 0.10$) strengthened 10 and 12 weeks after planting, respectively. In weeks 8, 10, and 12 the summit position had a lower NDVI value than the floodplain (Table 1). Differences in NDVI values and landscape position ($P \leq 0.05$) were observed in 2011 begining six weeks after planting. Mean comparisons of NDVI values did not show differences in landscape position consistently until eight weeks after planting, with general inconsistencies attributable to weed pressure (Table 1). A correlation between landscape position and NDVI occurred six and eight weeks after planting in continuous corn and rotational corn respectively in 2011 (Table 2). In 2010, 589, 888, and 1205 growing degree days were accumulated by weeks 6, 8, and 10 respectively. In 2011, 567, 826, and 1242 growing degree days were accumulated by weeks 6, 8, and 10 were respectively.

Grain yield was correlated with NDVI measurements taken later during the vegetative development of corn rather than early in crop establishment (Table 2). In 2010 and 2011, the highest correlation ($r^2 > 0.80$) value between NDVI and grain yield under continuous corn management was identified eight weeks following planting (Table 2). A correlation between NDVI and grain yield was also identified in the rotational plots at week 12 in 2011 (Table 2). Increases in NDVI eight weeks after planting were correlated to increases in grain yield in continuous corn (Fig. 1).

Differences in grain yield were not affected by landscape position. A correlation between landscape position and grain yield was not identified. There was no difference in grain yield between landscape positions in 2010. Differences in yield between landscape positions were identified in 2011 ($P \leq 0.10$). The floodplain position yielded higher than all other areas of the landscape under continuous corn management (Fig. 3). Plots managed in the rotational treatments were less variable in yield than their continuous corn counterparts, where the backslope had the lowest yield of all landscape positions (Fig. 3).

Discussion

This study explored the effect of landscape position on NDVI and grain yield of corn. Landscape effects as evidenced by differences in grain yield and NDVI were not evident until 2011 which received 50 cm less rainfall during the growing season as compared to 2010. When interpreting NDVI samples' waiting until approximately 800-900 growing degree days have accumulated is critical in order to successfully distinguish changes in growth patterns. NDVI measurements taken after 800 growing degrees days have accrued correlate more closely to grain yield than measurements taken earlier in the growing season. The results of this study support previous research showing that NDVI can be used as a nondestructive method to identify plant stress and differentiate corn growth across a landscape.

Adequate moisture can reduce the impact of soil variations on crop growth (Timlin et al., 1998; Kravchenko et al., 2005). During the 2010 growing season landscape position did not affect NDVI or grain yield. Conversely, during the 2011 growing season plots received considerably less rainfall potentially causing plant stress. Differences in NDVI throughout the 2011 growing season were associated with differences in landscape position. Variations in the growth of corn at different landscape positions can be related to inadequate fertility (Eck, 1984; Jacobs et al., 1991), high temperatures, and dry conditions (Fulton 1970; Herrero et al., 1980;

Dwyer, et al. 1992; Crafts-Brandner et al., 2002). Soil characteristics, production history, and topography influence the magnitude of plant stress (Timlin et al., 1998; Kravchenko et al., 2000; Jiang et al., 2004; Kravchenko et al., 2005). Any limiting factor integral to plant development can result in a reduction in plant growth.

These findings support the use of NDVI as an effective method to characterize a landscape, in-season, into areas of differential growth. Environmental conditions may have affected the relative efficacy of using NDVI during the 2010 growing season, however, mean comparisons beginning eight weeks following planting showed differences in NDVI based on landscape position (Table 1). Differences in NDVI between landscape positions were shown throughout the 2011 growing season (Table 1).

Aligning sampling date with total accumulated growing degree days was critical in associating NDVI with differences in landscape positions. Mean comparisons for both 2010 and 2011 show differences at week eight were common to both growing seasons (Table 1). This was supported by a correlation between NDVI and landscape position during both years at week eight (Table 2). While the absolute value varied slightly, approximately 800-900 growing degree days had been accumulated both years eight weeks after planting. These findings were consistent with previous research that indicated sampling at the mid-vegetative stages (V6-V7) being critical in differentiating between hybrids and tillage practices (Hatfield et al., 2010).

The sampling period that best identified disparities in landscape position was similar but not mutually exclusive with differences in grain yield. While a landscape position effect on grain yield was not established, a relationship between NDVI and grain yield was shown to be noteworthy. Under continuous corn production, NDVI at week eight proved to be most correlated to grain yield. While absolute values of NDVI were different between years, a plotted analysis showed that the linear relationship between NDVI and grain yield remained relatively indifferent to these discrepancies (Fig 1.). This correlation was maintained for several sampling periods following. Similar to the relationship between NDVI and landscape position, the mid-vegetative period proved to have the most potential for describing variability in grain yield. In the rotational study a correlation between NDVI and grain yield was unable to be established until week 12. This period of sampling also was shown to have a different linear relationship as compared to continuous corn, making these results dissimilar to those produced under a monoculture. Defining the primary objective for using NDVI, as well as the field management history, is important for a researcher or producer before its use is implemented.

Mean grain yield at different landscape positions in 2011 increased in areas of potential moisture, nutrient, and organic matter deposition. The floodplain, shoulderslope, and toeslope positions had higher grain yields then the summit, and backslope positions (Fig. 2). The floodplain and toeslope were located at lower elevations then the summit, shoulder, and backslope. The shoulderslope was located directly above a parallel terrace, in relation to the sloping landscape. This landscape effect on grain yield was reflected in the mean comparison of NDVI measurements in 2011 10 weeks after planting (Table 1). The floodplain and toeslope had greater NDVI values then other landscape positions, followed by the shoulderslope. The summit and backslope positions had the lowest NDVI values at that sampling period.

This study, in addition to previous research (Timlin et al., 1998; Kravchenko et al., 2000; Jiang et al., 2004; Kravchenko et al., 2005; Hatfield et al., 2010), provides a reasonable basis for the implementation of NDVI for in-season characterization of variations in corn growth across a variety of practices and environmental conditions. The implications of these findings have great potential benefits for those involved in the commercial production of corn. While high resolution NDVI was tested in this study, information can also be obtained from satellites. Additional research is needed on similar characterizations using remotely sensed data acquired from satellite imagery. The ability to identify areas of low productivity remotely could allow for the prioritization of practices such as integrated pest management, and fertilizer application. Assuring that measurements are taken at the mid-vegetative stage, reached at approximately 800-900 growing degree days, is critical in evaluating the accuracy of any resultant NDVI samples. Establishing a critical growing degree day for sampling makes it possible to accept remotely sensed information with knowledge of planting date, rather than ascertaining a specific stage of development. As the size of commercial production operations continue to grow, the ability to quickly gather data regarding the status of a crop will be critical in making decisions that are agronomically sound, environmentally friendly, and economically feasible.

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Table 1. Progression of normalized difference vegetative index (NDVI) for corn (*Zea mays* L.) across a landscape in 2010 and 2011. Values are means of observations from three experimental units at each of five landscape position during the indicated week following planting.

	Measure of NDVI (weeks after planting)[z]					
Landscape Position	3	4	6	8	10	12
2010[y]						
Summit	0.423 a[x]	0.453 a	0.370 a	0.557 b	0.723 b	0.673 b
Shoulder	0.363 a	0.473 a	0.377 a	0.590 ab	0.737 ab	0.687 ab
Backslope	0.350 a	0.407 a	0.363 a	0.597 ab	0.730 ab	0.673 b
Toeslope	0.397 a	0.440 a	0.370 a	0.583 ab	0.740 ab	0.717 ab
Floodplain	0.363 a	0.417 a	0.353 a	0.660 a	0.767 a	0.730 a
2011[w]						
Summit	0.348 b	0.335 bc	0.310 b	0.407 b	0.657 c	0.728 ab
Shoulder	0.422 a	0.390 ab	0.322 b	0.407 b	0.667 bc	0.735 ab
Backslope	0.355 b	0.325 c	0.313 b	0.413 b	0.665 c	0.725 b
Toeslope	0.360 b	0.334 bc	0.342 b	0.490 a	0.702 a	0.742 a
Floodplain	0.425 a	0.410 a	0.460 a	0.550 a	0.700 ab	0.735 ab

[z]Values represent the normalized ratio of irradiance reflectance in the visible and near infrared spectrums; the calculated value is unitless.

[y]n=15 experimental units, all treatments managed as a continuous rotation of corn.

[x]Means within columns followed by the same letter are not different at $P \leq 0.10$ according to Fisher's least significant difference (LSD) test.

[w]n=30 experimental units, 15 treatments were managed as a continuous rotation of corn and the remaining followed a double crop rotation of triticale (× *Triticosecale*) and soybeans (*Glycine max* L.).

Table 2. Pearson correlation coefficients describing the linear dependence between weekly normalized difference vegetative index (NDVI) of corn (*Zea mays* L.), landscape position and grain yield. The results from 2010 and 2011 are presented. Each rotation within the designated year was composed of 15 experimental units across 5 landscape positions with 3 experimental units at each.

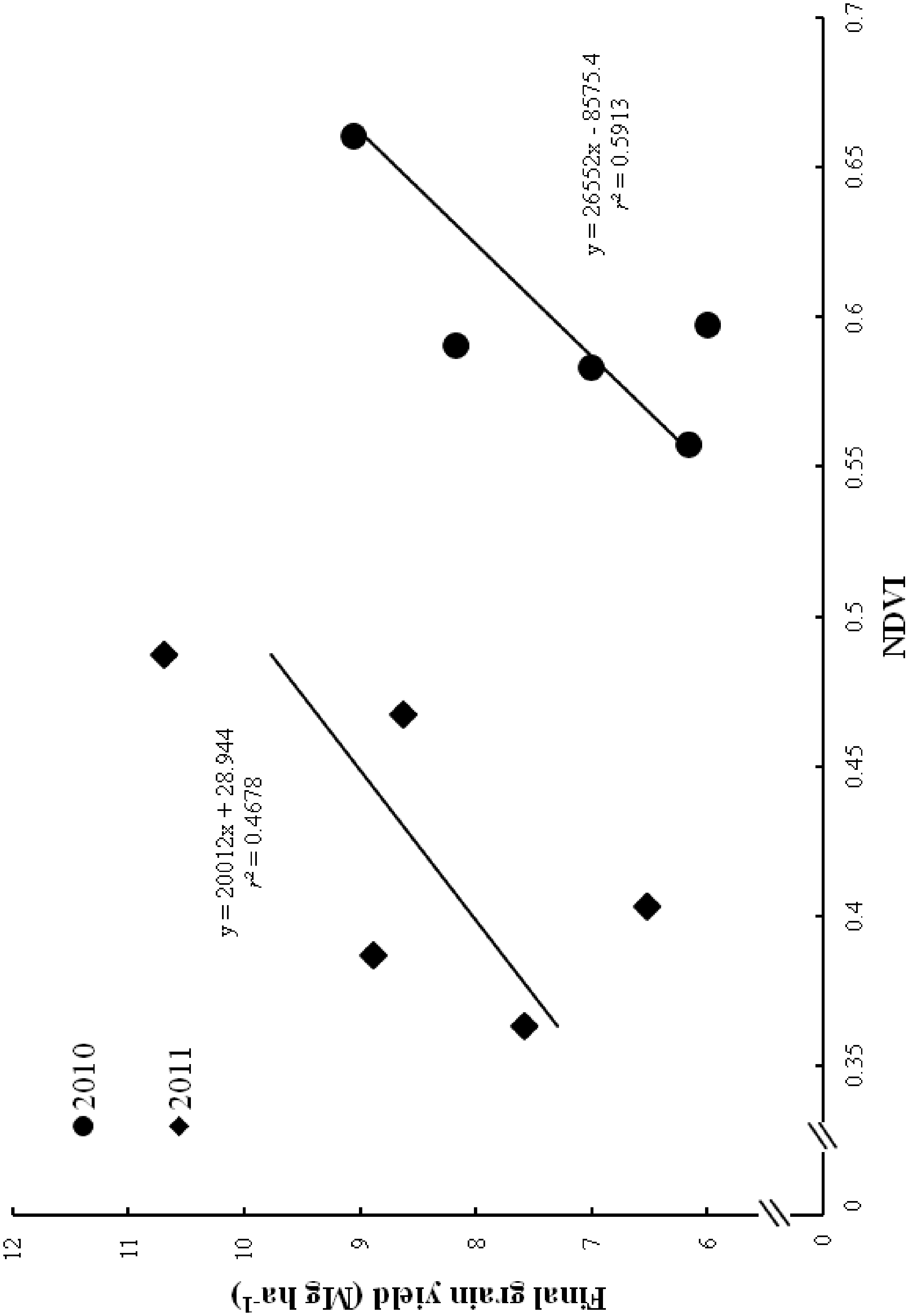
	Correlation Coefficients (NDVI weeks after planting)					
	3	4	6	8	10	12
2010						
Continuous Corn						
Landscape Position	-0.289	-0.227	-0.163	0.458*	0.535**	0.618**
Grain Yield	0.0841	-0.161	0.505*	0.883***	0.807**	0.472*
2011						
Continuous Corn						
Landscape Position	-0.0215	0.0812	0.735**	0.699**	0.413	0.130
Grain Yield	0.244	0.0376	0.382	0.816**	0.780**	0.700**
Rotational Corn						
Landscape Position	0.467*	0.408	0.493*	0.688**	0.654**	0.293
Grain Yield	0.365	0.115	0.278	0.136	0.0156	0.591*

*, **, ***Significant at $P \leq 0.10$, 0.05, or 0.001, respectively.

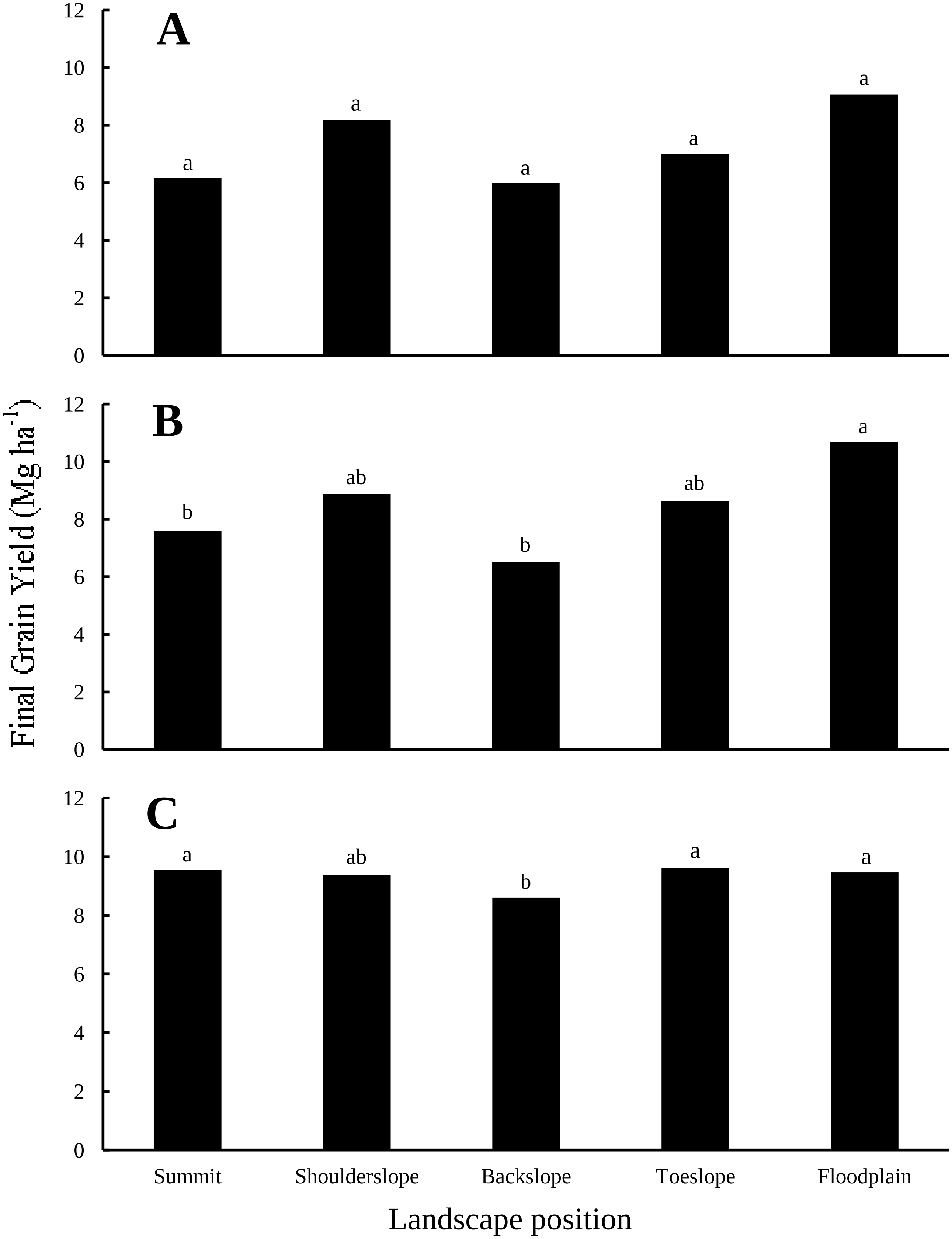
Figure Captions

Fig. 1. Linear comparison of normalized difference vegetative index (NDVI) of corn (*Zea mays* L.) 8 weeks after planting plotted against grain yield (Mg ha^{-1}) in 2010 and 2011. Values represent mean of observations from three experimental units at each of five landscape positions. All 15 experimental units were managed as continuous rotation of corn.

Fig. 2. Comparisons of grain yield by landscape position, year, and rotation. Observations represent mean grain yield of three experimental units from each of the five landscape postions. Subset **A** and **B** depict the 2010 and 2011 cropping seasons respectively and were managed as a rotation of continuous corn (*Zea mays* L). Subset **C** depicts 2011 grain yield of corn from plots managed in rotation with triticale (× *Triticosecale*) and soybeans (*Glycine max* L.) the previous cropping season. Means within year and rotation with the same letter are not different at $P \leq 0.10$ according to Fisher's least significant difference test (LSD).


Final grain yield (Mg ha-1)
NDVI
2010
2011
y = 26552x - 8575.4
r2 = 0.5913
y = 20012x + 28.944
r2 = 0.4678
0
6
7
8
9
10
11
12
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7

(Fig. 1)


A
B
C
Final Grain Yield (Mg ha-1)
12
10
8
6
4
2
0
a
a
a
a
a
b
ab
b
ab
a
a
ab
b
a
a
Summit
Shoulderslope
Backslope
Toeslope
Floodplain
Landscape position

(Fig. 2)

CHAPTER IV: CONCLUSION

Normalized differene vegetative index (NDVI) can be used to differentiate plant growth across a landscape in corn. NDVI measurements, taken approximately 800-900 growing degrees following planting, can be correlated to different landscape positions. These differences in plant growth are representative of the spatial distribution of plant stress across a landscape. The underlying causes of variations in plant stress are not determinable through use of NDVI currently. Remotely sensed information can accurately identify areas of reduced plant growth, relative to other areas in a management zone, indicating greater levels of plant stress.

Areas of greater yield potential can be accurately identified by using NDVI early in a growing season. NDVI values taken approximately 800-900 growing degree days following planting are correlated with yield differences across a landscape in continuous corn rotations. Greater NDVI values taken at this time related to higher grain yields. Measurements taken later (> 1200 growing degree days after planting) are more correlated to grain yield in corn grown in rotation with other crops. More research is necessary; evaluating any potential differences in NDVI values from corn grown in various rotations.

Incorporating technological advancements into an integrated direct approach to agricultural management will be required in order to meet the global demands of crop productions sustainably. Increased global demand, environmental protection, and crop production in increasingly marginal lands necessitates a focus on mitigating crop stress. Industrialized agriculture’s adoption of such practices as yield monitoring and soil sampling demonstrates an increasing awareness of spatial variability within many producer’s fields. The current desire of many involved with production agriculture to accrue data, expresses the potential for increasing efficiency through increased knowledge.

NDVI has the potential to provide producers and industry leaders the opportunity to build their databases and gain an intimate knowledge of the land under their management. As demonstrated through this study the potential of using NDVI to characterize corn production is present. Collection of NDVI data during the mid-vegetative period will allow producers and researchers to identify areas of greater environmental stress and lower plant productivity.

The possibilities of using NDVI and remotely sensed imagery are great. The possibility exists for NDVI to change agriculture management practices. However, more research is needed on the relationship between NDVI and other crops such as soybeans. Expansion of this type of study to multiple locations would subject the potential of NDVI to more environmental constraints. Evaluation of NDVI acquired through satellite imagery would help define the appropriate resolution required to characterize an area. As new sensors are introduced, their potential will need to be rigorously tested and put into the context of production agriculture as we have done with NDVI.

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