Assessment of Spectral Reflectance as Part of a Variable-Rate Nitrogen Management Strategy for Corn

Emily Kathryn Lewis

Thesis submitted to the Faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of Master of Science

In Crop and Soil Environmental Sciences

__________________________
Dr. Steven B. Phillips

__________________________
Dr. Gregory L. Mullins

__________________________
Dr. Marcus M. Alley

02 August 2004
Blacksburg, VA
Assessment of Spectral Reflectance as Part of a Variable-Rate Nitrogen Management Strategy for Corn

Emily Kathryn Lewis

Abstract

Spectral reflectance-based, remote sensing technology has been used to adjust in-season nitrogen (N) fertilizer rates for wheat to account for spatial variability in grain yield potential at a sub-meter resolution. The objective of this study was to examine the relationships among spectral reflectance indices, corn tissue N content, chlorophyll measurements, plant size and spacing measurements, and grain yield to develop a similar strategy for variable-rate N management in corn. Irrigated and non-irrigated studies were conducted during the 2002 and 2003 growing seasons in eastern Virginia. Plots were treated with various rates of preplant, starter, and sidedress N fertilizer to establish a wide range of grain yield potential. Spectral measurements, tissue N, chlorophyll measurements, and plant physical measurements were collected at growth stages V6, V8, and V10. At maturity, grain yield was determined and correlated with in-season data and optimum N rate to calibrate in-season, variable-rate N fertilization strategies. Results from these studies indicate that spectral reflectance is well correlated with plant N uptake and chlorophyll meter readings and can also be correlated with final grain yield. These relationships may be used to develop a model to predict in-season, variable N application rates for corn production at a sub-meter resolution.
Acknowledgements

I wish to recognize firstly the contributions of my committee chair and advisor, Dr. Steve Phillips. His counsel, understanding, patience, and guidance have been greatly appreciated as I have explored a fascinating project and progressed in my understanding of those processes and procedures required for quality professional research.

My appreciation also is expressed to Dale A. Keahey, Jason G. Warren, and Chad J. Penn, who assisted me frequently in the retrieval, analysis, and presentation of information used in this project and in respect to the finer points of being a graduate student.

I am grateful for the contributions of J.T. Custis, Jr., whose experience, knowledge, and time were significant factors that accomplished much of the field work for this experiment.

Thanks to Dr. Mark Alley and Dr. Greg Mullins, who have been greatly supportive and flexible in their guidance and analysis of my studies and achievements.

To JC Cloe, my sincere appreciation for the patience, abundant service, and genuine love which supported me in my times of extended effort.

Finally, I am inexpressibly grateful for my parents and sisters, whose unwavering love and constant care continually give me the faith and courage to do all that I do.
# Table of Contents

Abstract

Acknowledgements............................................................................................................iii

Table of Contents................................................................................................................iv

List of Tables......................................................................................................................vi

List of Figures...................................................................................................................viii

Literature Review.................................................................................................................1

   Methods for Improving Nitrogen Use Efficiency....................................................1

   Spatial Variability....................................................................................................4

   Defining the Field Element......................................................................................5

   Management of Variability......................................................................................6

   Soil Testing and Tissue Analysis............................................................................6

   Site-Specific Management Zones........................................................................7

   Remote Sensing........................................................................................................9

      Yield Mapping....................................................................................................9

      Aerial Photography..........................................................................................10

      Chlorophyll Meter..........................................................................................11

      Spectral Reflectance.......................................................................................11

   Overall Objectives.......................................................................................................16

   Chapter One: Spectral Reflectance as an Indicator of Corn Nitrogen Status..........17

      Introduction.......................................................................................................17

      Objectives.........................................................................................................18
Chapter Two: Use of NDVI to Estimate Yield and Determine Variable N Rates in Corn

Introduction ............................................................................................................ 30
Objectives .............................................................................................................. 32
Materials and Methods ........................................................................................... 32
Results and Discussion .......................................................................................... 34
Construction of grain yield prediction models ................................................... 34
Evaluation of grain yield prediction models – dryland corn.............................. 34
Evaluation of grain yield prediction models – irrigated corn............................ 35
Optimum N rate determination ............................................................................. 37
By-plant N fertilization ......................................................................................... 39
Conclusions ............................................................................................................ 40

Chapter 3: Summary and Conclusions ................................................................. 48
References .............................................................................................................. 50
Vita ......................................................................................................................... 61
List of Tables

Table 1.1. Selected soil chemical properties of Bojac sandy loam (coarse-loamy, mixed, semiactive, thermic Typic Hapludult) soil at Eastern Shore AREC, Painter, VA. ................................................................................................................................24

Table 1.2. Treatment structure of irrigated and dryland corn experiments in 2002 and 2003, Painter, VA.................................................................25

Table 2.1. Dryland corn grain yields (AY) in 2003 compared to predicted yield without additional fertilizer (YP_0), predicted yield with optimal additional fertilizer (YP_N), and predicted yield with optimal fertilizer using an adaptation of YP_N suited to the Mid-Atlantic region (YP_{N2})...............................................................42

Table 2.2. Irrigated corn grain yields (AY) in 2003 compared to predicted yield without additional fertilizer (YP_0), predicted yield with optimal additional fertilizer (YP_N), and predicted yield with optimal fertilizer using an adaptation of YP_N suited to the Mid-Atlantic region (YP_{N2})...............................................................43

Table 2.3. Recommended N rate (RNR) for 2003 irrigated corn as calculated using YP_N (predicted yield with optimum additional fertilizer) and YP_{N2} (predicted yield with optimum additional fertilizer as adapted to Mid-Atlantic region). Actual grain yields obtained under varying starter N treatments with no additional N applied (No N) or with optimal N rates (+N) applied, in addition to resultant nitrogen use efficiency (NUE), are also shown.........................................................44
Table 2.4. Recommended N rate (RNR) for 2003 irrigated corn as calculated using $\text{YP}_{N2}$ (predicted yield with optimum additional fertilizer as adapted to Mid-Atlantic region) and range of rates actually applied to individual plants receiving varying levels of starter N fertilizer. Also shown are actual grain yields when plants were fertilized on a by-plant basis or according to a fixed rate for multiple plants......45
List of Figures

Figure 1.1a. Corn N uptake related to NDVI in irrigated plots at growth stage V6 (2003). ............................................................................................................................................................................26

Figure 1.1b. Corn N uptake related to NDVI in irrigated plots at growth stage V8 (2003). ............................................................................................................................................................................27

Figure 1.2. Corn chlorophyll meter readings correlated with NDVI in irrigated plots at growth stages V6 and V8 (2003). Third line represents the regression equation obtained when data are regressed without respect to growth stage.......................28

Figure 1.3. Plant height (cm) correlated with NDVI of irrigated corn plants (2003).......29

Figure 2.1. Relationships between 2002 corn grain yield and NDVI measurements at growth stages V8 and V10 divided by days after planting (DAP).........................46

Figure 2.2. Relationships between 2003 corn grain yields and NDVI measurements at growth stages V4, V6 and V8 divided by days after planting (DAP).................47
METHODS FOR IMPROVING NITROGEN USE EFFICIENCY

Perhaps the most common tool that producers have utilized to determine N fertilizer application rates is yield goal. Dahnke et al. (1988) defined a yield goal as simply the “yield per acre you hope to grow”. The concept is basically to consider the maximum and minimum yields obtained in recent years on a certain field, remove the single highest value and lowest value, and then calculate an average yield. This number is then altered based on a prediction of environmental factors for the coming season such as temperature, precipitation, and moisture availability—the grower must forecast whether the conditions will be particularly ideal or stressing for crop growth. By combining this estimate with both an assessment of current soil N conditions (such as the results of a soil NO₃-N test) and an estimate of plant fertilizer N use efficiency (NUE; percentage of applied N fertilizer that is removed in the harvested portion of the crop), one may determine a rate of fertilizer that supposedly will be sufficient to obtain the yield goal under those expected conditions. Not only does this technique rely to a great degree upon prediction of unforeknowable events, but it usually also involves a single-rate N application to the entire field. To believe this method to be effective, one would have to assume that all areas of the field are equal in terms of production capacity and N requirements. This is certainly not the case and applying N at a rate averaged for the entire field can result in misapplication to several hectares and often very low NUE.

Nitrogen use efficiency for cereal grains is approximately 33% worldwide (Raun and Johnson, 1999). This number is a result of numerous nitrogen (N) loss pathways that are inherent within the cycling of N in the soil matrix. Current management practices that either enhance or fail to reduce losses via these mechanisms contribute significantly to yield reduction, decreased economic profits, and contamination of ground and surface waters. Several methods to counteract the negative effects of inefficient N use have been investigated. Among these are crop rotations, conversion of grain production systems to forage production systems, improved hybrids or cultivars, conservation tillage, NH₄-N
sources, in-season and foliar-applied N, and irrigation. Each of these methods meet with limited success.

The use of crop rotations is a commonly recommended practice that is based on the idea of maintaining higher levels of N in the soil for uptake by subsequent crops while lessening the amounts of applied fertilizer needed to supplement growth. Huang et al. (1996) showed that the use of a soybean \textit{Glycine max} (L.) Merr.–corn \textit{Zea mays} L. rotation as compared to continuous corn resulted in NUE and reduced residual soil N that could be leached. However, an obvious disadvantage of this method for improved N use efficiency is the need for additional equipment and different techniques for production of the subsequent crops.

Forage production systems involve harvesting the plant before it reaches the flowering stage and results in a reduction of plant gaseous N loss (Altom et al., 1996). While NUE could be increased by converting grain acreages to forage production (O’Leary and Rehm, 1990), forage is specifically consumed by the animal population. Hence, if conversion were to be implemented on a wide regional scale, our overall human food consumption would become more dependent on animal products instead of vegetative matter (Raun and Johnson, 1999). This, then, is perhaps the most radical and impractical of the suggested methods for improving NUE.

Plant breeding can be used to isolate characteristics of improved N uptake and efficiency, and differences in NUE among corn hybrids is usually due to the utilization of accumulated N prior to anthesis (Moll et al., 1982). One of the limitations of current breeding practices is that genetic selection is often done under high fertilizer N conditions, which makes it difficult to distinguish differences in efficiency (Kamprath et al., 1982). Raun and Johnson (1999) suggest greater need for plant selection under low N fertilizer conditions. This proposal is reinforced by Presterl et al. (2003), who state that, in attempts to improve NUE, direct selection of corn cultivars under low N conditions is more efficient than indirect selection under high N conditions.

Conservation tillage is looked upon as an environmentally-considerate method of production that has been increasing in popularity. Its attributed benefits include reduced erosion, lower operation costs, and lessened environmental impact. No-till in particular is cited by Bakhsh et al. (2000) as being the least-intensive tillage practice, leaving a
system of macropores and root channels which, combined with evaporation-limiting mulch from the previous crop, results in greater soil water content and deep percolation rates. Work by Thomas et al. (1973) showed how these characteristics of no-till are related to increased nitrate leaching in corn and therefore possibly necessitate increased N fertilizer rates for obtaining yields similar to conventionally-tilled corn.

Using a NH$_4$–N source of fertilizer has many apparent advantages. It requires less energy to assimilate into plant protein (Salsac et al., 1987) and is less prone to leaching and denitrification than NO$_3$–N (Tsai et al., 1992). Pan et al. (1984) showed that there was little difference between calcium nitrate and urea fertilizer sources in regards to N uptake and grain yield in corn at low (56 kg N ha$^{-1}$) rates. However, at high (224 kg N ha$^{-1}$) rates, uptake and yield increased when urea fertilizer was used. Also, they found that when the corn plant is unable to absorb NO$_3$–N at the time of ear development, it can take up NH$_4$–N. So NH$_4$–N can be made available in the late season to reduce the likelihood of related yield limitation. Care must be taken not to apply NH$_4$–N in excess nor with inappropriate timing, however, because high levels will result in retarded growth and restricted uptake of K$^+$ (Havlin et al., 1999).

Putting down a single, high-rate application of N fertilizer prior to or during the time of planting is a convenient practice implemented by some growers. Still, NUE decreases with increasing N rates and much of the applied N may not be available for plant uptake later in the season during the critical period; for corn, this is just prior to the tasseling stage (Hanway, 1963). After initially applying a small amount of N for the early growth stages, a second, in-season N fertilizer application can be adjusted to meet the anticipated needs of the crop at a growth stage closer to the occurrence of this critical period. Many growers, however, are not willing to make a second application later in the season. For some, this may be because of the fear that possible N stress before the later application can be made will cause permanent reduction in yield. Others are opposed to the potential requirement of high-clearance equipment. A few may object to making time in their schedules or setting aside money in their budgets for the additional application. However, splitting N applications in corn production has met with considerable success in many states, including Virginia (Evanylo, 1991; Alley et al., 1997), Ohio (Eckert and Martin, 1994), and Minnesota (Randall et al., 2003). These studies report greater NUE,
either greater yields or no reduction in yield compared to more conventional fall or spring applications, and greater economic return on fertilizer as a result of using sidedress N fertilizer.

Areas of heavy rainfall or fields under irrigation systems are subject to loss of N via NO₃⁻ leaching. Smika et al. (1977) measured nitrate concentrations in water percolating to a 150-cm depth in corn experiments. After finding a strong negative correlation of average annual total dry matter production with the percolated nitrate, they concluded that production was highly related to nitrate loss. In this experiment, total dry matter production decreased 65 kg ha⁻¹ for each kg ha⁻¹ of nitrate that reached the 150-cm depth. Increasing NUE in irrigated production of corn is accomplished by means of light, frequent watering with low in-season N rates (Russelle et al., 1981). Eghball and Maranville (1991) emphasized that, in corn, NUE was usually congruent with water use efficiency (WUE).

**SPATIAL VARIABILITY**

Techniques for managing NUE tend to focus on optimizing specific aspects of production that are limited by locale, microclimate, financing, and technology. However, they almost all are implemented primarily under the conventional practice of applying N fertilizer at a single rate. Within most every field, it is apparent that not every area produces similar yields (Raun et al., 1998b). This effect may be due to either inherent or man-made sources of spatial variability, such as water holding capacity and yield potential, as well as temporal variability. Spatial variability, particularly in soil chemical properties, may be one main reason for this difference in productivity. Specifically, areas of the field have varying capacities to supply crop mineral nutrients, and subsequently, yields may differ from one section of the field to the next. When a single rate, “blanket” application is made, locations within the field, which may be either already sufficient in the nutrient or greatly deficient, may respectively receive either too much fertilizer or too little. In order to optimize fertilizer inputs, the grower would do well to consider managing these areas independently, applying only the amount of fertilizer that is necessary in each area.
DEFINING THE FIELD ELEMENT

Research has been conducted to determine at what scale nutrient variability exists and must potentially be treated. Solie et al. (1996) defined a fundamental field element as “that area which provides the most precise measure of the available nutrient where the level of that nutrient changes with distance”. Raun et al. (1998b) built upon that definition to describe the ideal field element size for precision agriculture production as being able to identify:

1. “The smallest resolution at which cause and effect relationships can be defined”;
2. “The precise resolution at which variances between paired samples of the same size (area) become unrelated (use of semivariograms) and where heterogeneity can be recognized”;
3. “The resolution at which misapplication could pose a risk to the environment”;  
4. “The treated resolution at which net economic return is achieved (inputs exclude the cost of technology)”; and
5. “The resolution at which differences in yield potential may exist.”

Numerous researchers have attempted to determine the parameters of such a field element and results have suggested that this area has become progressively smaller. Chancellor and Goronea (1994) found evidence to advocate the need to measure and treat variability at a resolution of less than 1m$^2$. In their study of winter wheat (*Triticum aestivum* L. emend. Thell), N application at < 1m$^2$ intervals resulted in a 12% increase in NUE. When considering bermudagrass at the submeter level, Raun et al. (1998b) found significant differences in surface soil test analyses for both NO$_3$-N and P and also found large differences in forage yield. The necessity of these submeter dimensions for a fundamental field element for precision management of soil variability have been since confirmed and supported by other studies (Solie et al, 1999; Lukina et al, 2001; Raun et
Effective management of existing microvariability therefore requires technology that will function at such a scale.

MANAGEMENT OF VARIABILITY

Soil testing and tissue analysis

Soil testing is perhaps the most widely-used method of determining soil N content, and is commonly done to ascertain the amount of supplemental nutrient that should be provided to the plant for adequate growth and production. However, due to the numerous pathways that chemically and physically route N within the soil during the early periods of the growing season, pre-season soil N testing is not adequate as a one-time evaluation that will cover the crop’s needs for the entire season (Evanylo and Alley, 1998). Specifically, NO$_3$-N is highly leachable and subject to runoff and denitrification, so it becomes necessary to consider the additional application of fertilizer after the plant has begun its growth.

The pre-sidedress soil nitrate test (PSNT) (Magdoff et al., 1984) is a method used by many regions to monitor the availability and/or mineralization of the preplant- or starter-applied fertilizer or soil N, particularly if the field has a history of manuring or if corn follows a legume in rotation (Evanylo and Alley, 1998). The results of the test are used to evaluate supplemental N fertilization needs for corn after germination and before the period of greatest need—approximately 30 to 45 days after emergence (Evanylo and Alley, 1998). Implementation of this test in Virginia involves sampling 10 to 20 cores across the field at a depth of 30 centimeters, while avoiding starter bands and areas of root depletion. This composite sample is then analyzed for NO$_3$–N and sidedress N recommendations are adjusted based on the results (Evanylo and Alley, 1998). Durieux et al. (1995) showed that PSNT has certain advantages over yield goals for making lower N fertilizer recommendations without sacrificing grain yield quantity. However, this test is based on the composition of a relatively few number of samples per field; therefore, though it was not designed to do so, it does not adequately describe, nor provide means for treating, detailed within-field nutrient variability.
One soil sampling method that may improve the practicality of soil testing is the practice of grid sampling, in which equally spaced soil samples are collected throughout the field and then analyzed separately. Grids of 0.8 to 1.2 hectares are common, though they may range from 0.4 to 2.0 hectares (Havlin et al., 1999). Samples may be collected from within a cell and composited, but this averaging does not allow for a perspective on variability. Instead, point sampling may be used. At each intersection of grid lines, samples are collected from a 3-m-diameter circle, which supposedly accounts for variability (Havlin et al., 1999). However, this method of soil sampling is dependent on grid size to accurately describe variability; too large a grid would be inadequate, and too small a grid would increase the expenses of having the greater number of samples analyzed.

Likewise, in-season tissue N content analysis may be a highly accurate means of directly determining plant N concentrations and uptake, which may be correlated with yield and used to suggest fertilizer recommendations. Several states including Michigan (Vaughan et al., 1990), Arkansas (Adams et al., 1985), and Maryland (Meisinger et al., 1987) use either tissue testing or soil NO₃-N measurements to make field-specific N fertilizer recommendations for wheat. In Virginia, tissue testing is a primary aid in determining fertilizer N recommendations for wheat (Scharf and Alley, 1993; Scharf et al., 1993). Reported potential profits from using tissue testing in this system were $73 ha⁻¹ (Scharf and Alley, 1993). However, the scale at which tissue testing is performed must, as with soil testing, be taken into consideration— a larger sampling area means fewer samples to represent the larger potential for variability and the subsequent averaging masks variability, while too many samples incurs higher costs for analysis. Even if expenses were not a limitation to this procedure, it still does not provide a means for treating variability at the scale it exists.

**Site-specific management zones**

Another technique for managing soil variability is that of site-specific management zones (SSMZ), defined as “specific areas within a field that respond to management practices in a similar way” (Elstein, 2003). In a study to demonstrate the advantage of using SSMZ for precision agriculture, Khosla et al. (2002) suggested the
need for yield history, soil color from aerial photographs, topography, and producers’ management experiences in order for this method to be effective. They used the latter three as parameters for their own experiment, and incorporated the data layers into a geographic information system (GIS) database, which then ran a mathematical interpolation to define the management zones. When compared to yield goal-based, conventional uniform-rate treatments, and grid-based systems, the SSMZ method as utilized by Khosla et al. (2002) showed improved yield optimization and NUE.

Franzen et al. (2002) investigated soil surveys that are frequently used as a basic layer of information for determining management zones. Most surveys are Order 2, with minimum size delineation of 0.6 to 4.0 ha. Order 1 surveys are designed to include more detail and use minimum size delineations less than 1 ha. The authors analyzed the usefulness of these two orders in regard to determining zones for variable-rate NO$_3$–N management. They found Order 2 surveys to be insufficient alone for this purpose, as their inclusive information is too general. Order 1 surveys were more useful, but not as consistently well-correlated to NO$_3$–N as zones determined by topography or 2.5 sample ha$^{-1}$ grid sampling. They therefore recommended the use of Order 1 surveys in addition to other information layers, such as those suggested by Khosla et al. (2002). Fraisse et al. (2001) specifically examined topography and soil electrical conductivity parameters in claypan soils and determined these to be the most important considerations when determining zones, and suggested this information should be supplemented with information layers of crop scouting, disease and insect damage, pH, and soil fertility.

Chang et al. (2004) examined four methods of determining zones and how well they minimized yield variability and fertilizer recommendation errors in the field. Using an Order 1 soil survey and a 4-ha grid cell to define zones reduced yield variability more effectively than all other methods tested, which were based on physical properties and relative geographic location. In addition, lower N rates were recommended for the Order 1 soil survey method than for the grid cell method.

One of the limitations of SSMZ lies in the fact that this technique distinguishes zones on ordinal ranking scales such as the “low”, “medium”, and “high” production areas used by Khosla et al. (2002). It does not have the capacity to segregate the number of zones as would be needed to determine—much less suggest a method for treating—the
soil variability that exists at a finer resolution. This technique lacks potential for efficient management at smaller scales such as 1 m². Also, although current GIS software is adept at managing multiple layers of information that are necessary for consideration in determining management zones, the acquisition of these data is a costly process and some data layers will probably need to be repeatedly collected each growing season.

**Remote Sensing**

Remote sensing is the acquisition of data at a physical distance from the unit whose properties are being described. It involves the use of engineered technology, which commonly utilizes a broad aspect of the electromagnetic spectrum. The variations in “flow” of these wavelengths when applied to the subject of study are monitored and recorded for further analysis. Remote sensing has found applications in agriculture as improved techniques are discovered and sensed data are more closely correlated with specific plant growth properties.

**Yield mapping**

Yield mapping involves using a sensor placed in a combine that measures the rate of mass flow of clean grain between the bottom of a clean grain elevator and a holding tank, while using the Global Positioning System (GPS), to determine the position of the combine in the field. These flow rates are used for estimations of yield that are referenced to the field location to develop a map that may be used to adjust fertilizer inputs within the field (Lark et al., 1997). Lark et al. (1997) suggest a number of limitations on the spatial resolution of this practice. First, the width of the cutter bar, typically 4 to 6 meters, determines the resolution of the map perpendicular to the direction of the pass. In the direction of the pass, resolution is limited by the frequency with which flow rates are recorded. Additionally, the authors point out the fact that some grain will fall through the system rapidly while some will linger. As a result, the flow measurement represents a function of yield along a length rather than actual yield at an actual point. Yield mapping holds some value as a tool which provides a quick view of the entire field and rapid identification of “problem areas” which yield poorly. However, Raun et al. (1998a) suggest that yield mapping in and of itself is insufficient as an
instrument for managing variability because the procedure is void of a cause and effect relationship, and therefore requires the separate analysis of such variable factors as soil testing, etc.

_Aerial Photography_

Data on field conditions can also be collected in an overhead view obtained from an aircraft as it passes over a designated area at a certain altitude. Either reflectance-based data or photographic film data are available using this method. Photographic film is the least expensive and most available of the two options, but the increasing availability of digital photography may quickly make film among the less convenient options (Plant et al., 2000). Either form of data has been beneficial for such uses as correlations with growth factors and yield, disease and insect damage tracking, and determining soil chemical properties (Shanahan et al., 2001; Plant et al., 2000; Chen et al., 2000). Scharf and Lory (2002) showed how aerial photography could be used to calibrate corn color to sidedress N need. However, the success of this study was dependent upon no N being applied at the time of planting, presence of a non-N-limiting reference strip in the field, and removal of soil pixels from the image. They listed a few other limitations described in this study which are typical of limitations concerning aerial photography in general when considering its use for N management. First, for the photography to be effective as a tool for management at the scale variability exists, a high-resolution image is required. Higher resolutions for more precise management increase operating expenses. Second, the image data are collected from heights of hundreds of meters above the actual surface to be treated, which allows for potential errors in relating aerial measurements to field-scale treatments. Greater heights could result in less precise recommendations. Also, the time required for processing and obtaining images and using them to prescribe variable-rate treatments could exceed the amount of time available for making sidedress N applications in the case of corn (Scharf and Lory, 2002). An additional concern is that aerial photography is only practical for use on cloudless to nearly cloudless days when a clear view of the field may be obtained.
**Chlorophyll meter**

Chlorophyll meters are used to determine the N status of a plant by measuring chlorophyll content through absorbance of light at certain wavelengths. The Minolta SPAD 502 chlorophyll meter emits light at two wavelengths, one of which is associated with chlorophyll absorbance, and the other is used for calibration. Wood et al. (1992) showed that SPAD meter readings are well-correlated with tissue N concentration in corn and that tissue N concentration is also well-correlated with grain yield. Therefore, it was proposed that by using a meter to determine chlorophyll content and estimate N concentrations, one may determine the need for N fertilizer. Varvel et al. (1997) did just the procedure by using a sufficiency index, which is the chlorophyll meter reading from a treatment that received N as needed divided by the maximum chlorophyll meter reading from treatments receiving fixed N rates. If the index was below 95 percent, a rate of 30 kg ha\(^{-1}\) N was applied to the corn. Using this method, as long as the sufficiency index at V8 was not below 90 percent, near maximum yields were obtained in most years of the study while often using less fertilizer than if the readings had not been taken. However, Piekielek and Fox (1992) found that while SPAD values are useful in corn for identifying which plants and areas will respond to sidedress fertilizer, they are not sufficiently accurate for determining specific N rates. Thus, while Varvel et al. (1997) showed that chlorophyll meters are useful for determining the need for N fertilizer and that applying N fertilizer when so indicated can result in maximum yields, they still used a fixed rate which did not address the specific variable N needs of the plants, as would probably occur in most fields. While the design of the study admittedly did not include an attempt to determine exactly how much fertilizer would be needed, it demonstrates that the applicability of this technology has limitations in respect to truly optimizing fertilizer use.

**Spectral Reflectance**

Reflected wavelengths of light in the near-infrared and visible regions of the spectrum have been combined in several plant vegetation indices: ratio vegetation index (RVI) (Jordan, 1969), plant nitrogen spectral index (PNSI) (Perry and Lautenschlager, 1984 and Duncan et al., 1993), and green normalized difference vegetation index
(GNDVI) (Gitelson et al., 1996). The most common is the normalized difference vegetation index (NDVI; Tucker, 1979). As early as 1982, Walburg et al. (1982) showed a difference of red and NIR wavelength reflectance in varying N fertilizer treatments of corn as evidence for the potential of using NDVI in monitoring crop nutrient stress. Normalized difference vegetation index has been shown to be highly correlated with early-season N uptake in wheat (Lukina et al., 2001) and has been used successfully by researchers in various ways to not only determine plant N content variability, but also to estimate yield for a variety of crops and to make optimum N fertilizer rate recommendations according to spatial variability (Raun et al., 1998b; Sembiring et al., 2000; Lukina et al., 2001; Raun et al., 2001; Osbourne et al., 2002; Raun et al., 2002).

Raun et al. (2001) showed how NDVI (obtained in-season) should be used to predict yield in winter wheat when the wheat would receive no further N application. They divided the sum of NDVI at the time of two readings by the number of growing degree days (GDD) between the two readings to produce an index for in-season prediction of grain yield (EY). The relationship between actual grain yield and EY resulted in $r^2 = 0.50$. This method was critiqued by Lukina et al. (2001) as being “cumbersome”, due to its necessity of taking two readings.

Lukina et al. (2001) proposed an alternate in-season estimated yield index (INSEY) that simply divided a single NDVI reading by the number of days from planting to sensing, achieving a coefficient of determination relating INSEY to wheat grain yield of $r^2=0.64$ as compared to the 0.50 coefficient reported by Raun et al. (2001). They then proposed a N fertilization optimization algorithm (NFOA) that used NDVI to recommend high rates of N fertilizer for areas with high yield potential and low rates of fertilizer for areas with lower potential. In this algorithm, potential grain yield was predicted using an exponential equation derived from the correlation of INSEY and actual grain yield. Percent N removed in the grain was estimated using an equation derived from empirical data. Multiplying these factors provided a prediction of grain N uptake. An estimate of plant N uptake at the time of sensing was obtained from a calibration of NDVI with total N uptake. This factor was subtracted from the predicted grain N uptake and the result (predicted N deficit) divided by a maximum efficiency factor of 0.70. The number
obtained by these calculations represented an in-season topdress fertilizer N requirement for wheat.

In 2002, Raun et al. developed another NFOA for wheat that utilized a response index (RI) in an effort to describe the potential yield increase that could be gained by applying N in-season at optimal rates. This index divided the NDVI of a strip of land that was not N supply-limited by the NDVI of a parallel strip that had been fertilized according to the grower’s standard practice. The number RI multiplied by predicted grain yield potential without additional fertilization (YP₀) (Lukina et al., 2001) gave an estimate of potential yield with added N fertilizer (YP₅). Estimates of percent N in the grain at harvest, grain N uptake, forage N uptake at the time of sensing, and the in-season fertilizer N requirement, were determined according to Lukina et al. (2001). Mullen et al. (2003) revised and improved this method for determining in-season fertilizer N requirement by recommending the subtraction of estimated grain N uptake at YP₀ from estimated grain yield uptake at YP₅, before dividing the result by an efficiency factor of 0.70. Thus, an estimate of forage N uptake was not required, as in Lukina et al. (2001) and Raun et al. (2002).

Some researchers have questioned using NDVI as a tool for monitoring crop growth because of its sensitivity to optical soil background influence. Rondeaux et al. (1996) described three factors of soils that make up this influence: color, roughness, and water content. Color variance is important to consider because inconsistency in color—and hence, light reflectance—of a soil background can skew data that will incorrectly be attributed to reflectance of the plant. The roughness of a soil implies uneven surfaces that scatter light waves and cast shadows, resulting again in an inaccurate sensor reading. Water absorbs light at different wavelengths and varying water content of soil may influence the perceived color. Thus, alternative indices have been developed: (SAVI) (Huete, 1988), (TSAVI) (Baret et al., 1989), (MSAVI) (Qi et al., 1994), and (OSAVI) (Rondeaux et al., 1996). These indices, however, are not widely used in practical application. Rondeaux et al. (1996) suggest that this may be the result of either the relative complexities of their formulas or because of a lack of adequate demonstration of their superiority over NDVI.
Also of concern regarding the implementation of spectral reflectance in general is its reliability for estimating grain yield under water-stressed conditions. Peñuelas et al. (1993) studied the relationship between plant water status and spectral reflectance, using a ratio R970 (nm)/R900 (nm), 970 nm being one of the water absorption bands. They found this index to be a useful indicator of water stress when relative plant water content was less than about 80 percent and water stress was already developed. The best results were obtained at the canopy level (versus individual leaves) and when the canopy was dense. Further work on this water band index (WI; Peñuelas et al., 1996) confirmed its being affected by cell wall elasticity, which in turn affects plant ability to adapt to water stress and was shown to vary in wheat according to N rate. Less N resulted in lower elasticity, which resulted in the improved ability of the WI to indicate water stress.

Osbourne et al. (2002) reported that water stress influences those wavelengths used to estimate plant N. They found that in water-sufficient corn, green (550 nm) and certain midinfrared (MIDIR) wavelengths best predicted total N tissue content ($R^2 = 0.95$) and biomass ($R^2 = 0.94$). In water-deficient corn, red (600 and 700 nm) and other MIDIR wavelengths best predicted total tissue N content ($R^2 = 0.87$) and biomass ($R^2 = 0.87$).

Spectral reflectance technology has the capability to detect N variability at a defined resolution of less than 1 m$^2$ (Lukina et al., 2001; Raun et al., 2002). Recently, it has also been enhanced with the ability to treat this variability at the same scale, which gives it advantage over all other proposed methods thus far. NTech Industries, Inc. (Ukiah, CA) has made commercially available the GreenSeeker® sensor unit that, with algorithms for determining needed N fertilizer rates, may be utilized with a combination of nozzles to sense and treat crop N deficiencies with variable rates on-the-go at the submeter level (Solie et al., 2002).

As the only currently existent method for treating spatial variability at such a scale, this technology holds great potential for increasing NUE as shown by Raun et al. (2002). In their study, NUE of all winter wheat plots that were fertilized at a variable rate using the NFOA either stayed the same or exceeded the NUE of plots that received single-rate treatments. Also, NUE increased more than 15% on plots that received no preplant fertilizer and a midseason N application according to the NFOA, compared to plots that received no preplant and 45 kg ha$^{-1}$ midseason N. Most recently, Phillips et al. (2004)
found that at two of their six sites, NUE was improved in early-spring N applications to winter wheat when sensor-based, variable fertilizer N rates were lower than those obtained under standard recommendation procedures without observing a reduction in grain yield.

This success encountered in work conducted on winter wheat suggests a need to explore application of the technology in other crops. While continuous winter wheat is a primary crop of the Great Plains region where these algorithms were developed into their currently functional forms (Raun et al., 2001; Lukina et al., 2001; Raun et al., 2002), it plays a much smaller role in the overall production of other regions. In the Mid-Atlantic region, for example, growers more commonly implement a corn-wheat-soybean rotation. Whereas winter wheat makes up 30 percent of the Great Plains’ (Oklahoma, Nebraska, and Kansas) total harvested land area (USDA–NASS, 2002), it only makes up 9.7 percent of total harvested land area in the Mid-Atlantic Coastal Plain (Virginia, Maryland, Delaware, and North Carolina; USDA–NASS, 2002). Great Plains corn is planted to 22.8 percent of its harvested land area (USDA–NASS, 2002), but Mid-Atlantic Coastal Plain corn represents 18.5 percent of the harvested land area (USDA–NASS, 2002), which is almost twice the total land area on which winter wheat is harvested in this region. If spectral reflectance-based, variable-rate fertilizer technology is expanded for use in additional crops, it may be more commonly accepted as a suitable, economical means for improving NUE.
Overall Objectives

The overall objective of this study was to develop a sensor-based, variable-rate N fertilization strategy for corn production in the Mid-Atlantic Coastal Plain. Specific objectives included i) examining the correlation among NDVI, chlorophyll meter readings, tissue N content, and physical plant characteristics at various growth stages, and ii) evaluating existing sensor-based strategies for yield prediction and optimum N rate determination.
Chapter 1: Spectral Reflectance as An Indicator of Corn Nitrogen Status

Introduction

Nitrogen fertilizer management is a major focus of efficient corn production. Overuse of N fertilizers causes economic and environmental hazards that can be avoided with careful application. Optimizing fertilizer N input requires applying no more and no less than the amount needed by the plants. This amount depends on spatial variability of plant available N within the soil. In-season plant and soil measurements may be made and used to determine the N status of the plant and surrounding soil. A knowledge of current N status under these conditions contributes to defining the subsequent need or lack thereof of further N fertilization.

The pre-sidedress soil nitrate test (PSNT; Evanylo and Alley, 1998) is used in Virginia to measure soil N in the form of nitrate (NO$_3^-$), which is one of the most readily available N forms taken up by corn. The PSNT is frequently used following application of organic fertilizer sources to monitor the mineralization of these N compounds. The measurements obtained in this test provide an in-season indication of whether additional N fertilizer will be needed to supply the plant for the remainder of its growth.

Tissue N content is perhaps the most direct method of determining how much N is being taken up by the plant. This is a destructive method in which the plant sampled is, dried, finely ground, and analyzed via combustion or other chemical processes (Westerman, 1995). Because N is a necessary component in the synthesis of proteins which are utilized in structural formation within the plant, biomass may also be an indicator of the plant’s N status. This, too, is a destructive method in which the plant is harvested, weighed, dried, and weighed again. It has the added advantage of providing a water content measurement. Biomass may in turn be estimated in corn by multiplying individual plant height by the width of the uppermost opened leaf to estimate individual plant area, or simply by referring to individual plant height alone. However, PSNT (Evanylo and Alley, 1998) and tissue N (Westerman, 1995) analyses, as well as biomass determinations, all require significant time for data collection, processing, and/or laboratory procedures to provide data useful in recommending N fertilizer needs.
Nitrogen is a major component of chlorophyll, which affects “greenness” of plant leaf tissue. Chlorophyll meters provide an indirect method of determining plant N content by using light wavelengths to indicate the presence of chlorophyll. Meter readings, specifically those of the SPAD meters (Minolta Camera Co., Ltd., Japan) have been relatively well-correlated with N content in corn (Wood et al., 1992; Blackmer et al., 1994). While this technique significantly reduces the time factor encountered in laboratory procedures when determining tissue N concentrations directly, it still requires the user to spend time in the field collecting data by hand on a plant-by-plant basis.

Normalized difference vegetation index (NDVI) is a measurement that is based on the reflection and refraction of near infrared and red light wavelengths on plants according to the equation

\[
\text{NDVI} = \frac{(\text{NIR} - \text{Red})}{(\text{NIR} + \text{Red})} \quad \text{[Eq.1]}
\]

Using a sensor that measures reflected light in the red and NIR wavelengths for calculating NDVI, such as the Greenseeker® (NTech Industries, Inc., Ukiah, CA), has the advantage, like the chlorophyll meter, of being non-destructive, as well as a very quick method that can sense differences at submeter levels as the sensor passes through a field. The benefits consequently include less time spent obtaining data and a more detailed description of actual field conditions. This technology has been applied to wheat in order to predict grain yields in-season and prescribe fertilizer rates to optimize N use (Lukina et al., 2001; Raun et al., 2001; Raun et al., 2002). To expand the function of NDVI for similar application in other high-acreage crops, it must first be calibrated with known estimates of plant N uptake in those crops. Those calibrations must then be examined to determine the time at which NDVI sensing best indicates plant N concentrations while still allowing for in-season applications of N fertilizer.

**Objectives**

The specific objectives of this study were i) to correlate NDVI with corn N uptake, chlorophyll meter measurements, and plant height and width of the uppermost opened leaf to determine its potential for use in developing N fertilization optimization
algorithms for corn, and ii) to determine the growth stage at which NDVI is best suited for estimating N uptake by corn within the time frame for subsequent sidedress N fertilization.

**Materials and Methods**

One irrigated and one dryland field experiment with corn was established each spring in 2002 and 2003 at the Eastern Shore Agricultural Research and Extension Center in Painter, VA. The production system utilized conventional tillage methods on a Bojac sandy loam (coarse-loamy, mixed, semiaactive, thermic Typic Hapludult) soil. All experiments used a randomized complete block design with three replications. Plots utilized 76-cm row spacing and consisted of either 4 or 6 rows. In 2002, plot length was 5.5 m, and in 2003, plot length was 4.6 m. Prior to planting, composite soil samples (0 to 15 cm) were taken from the experimental area and nutrients other than N were applied according to soil test recommendations (Donohue and Heckendorn, 1994). Initial soil test characteristics are reported in Table 1.1. Preplant incorporated ammonium nitrate fertilizer (34-0-0) was applied with a conventional drop-type spreader at rates of 0, 67, 135, 202, and 269 kg N ha⁻¹. Planting occurred on 02 May 2002 and 05 May 2003 using Pioneer brand hybrids 31G20 in 2002 and 32R25 in 2003 at seeding rates of 69,136 kernels ha⁻¹ in the irrigated experiments and 54,321 kernels ha⁻¹ in the dryland experiments. Starter N fertilizer was applied at planting at rates of 0, 34, 56, and 78 kg N ha⁻¹ as 30 % urea ammonium nitrate (UAN) solution. Sidedress N fertilizer was applied at growth stage V8 (Ritchie et al., 1993), using 30% UAN solution at 0, 56, 112, and 168 kg N ha⁻¹. This was accomplished using a Hagie high-clearance sprayer equipped with drop-tube nozzles that were spaced 76.2 cm apart and sprayed on both sides of the plants at the base, 2 rows at a time. The complete treatment structure is reported in Table 1.2. Irrigation was applied as needed, using a lateral-movement overhead sprinkler.

Normalized difference vegetation index (using red (671 ± 6 nm) and near infrared (780 ± 6 nm) wavelengths) measurements were collected from the plant canopy using a hand-held GreenSeeker® sensor (NTech Industries, Inc., Ukiah, CA). The sensor was centered over a row of plants and held approximately 0.9 m above the canopy while being moved along the row to record measurements.
In 2002, NDVI measurements were collected from a 0.9 m section of row in all 6-row plots (Table 1.2.) at growth stages V8 (irrigated and dryland) and V10 (dryland). The above-ground tissue from the sensed areas was harvested by hand, cutting at the base of the plant. The tissue was then dried at 65°C, ground to pass a 150-µm sieve, and analyzed for total tissue N content using a CE Instruments NC 2100 Dry Combustion Analyzer (CE Elantech, Inc.; Lakewood, NJ). Normalized difference vegetation index (NDVI) measurements were also taken at V8 in the 2002 irrigated study from 126 individual plants in a continuous row that had been fertilized in 5.5-m sections according to treatments 5, 13, 17, 19, and 20 (Table 1.2.). Chlorophyll meter readings were also taken on these plants using a Minolta SPAD 502 chlorophyll meter.

Normalized difference vegetation index (NDVI) measurements were collected at growth stages V6 and V8 on irrigated plots in 2003, but readings were made individually on 3 consecutive plants in a row of all 6-row plots (Table 1.2), instead of continuously over the row section, as in 2002, so as to provide opportunity to investigate whether individual sensing described more variability. The above-ground tissue from the sensed areas was harvested, processed, and analyzed as described above. NDVI measurements were also taken at V6 and V8 on each of 170 individual plants that had been fertilized according to treatments 1, 5, 9, or 13 (Table 1.2). Plant height and width of the uppermost fully-expanded leaf were also recorded at V6 and V8 for these plants. Relationships among variables were analyzed using linear regression, which was performed using PROC REG procedures (SAS Inst., 2000).

Results and Discussion

Relationship between NDVI and N uptake

In 2002, NDVI was regressed against N uptake (percent N * dry matter weight) at the V8 and V10 growth stages. At V8 in the dryland experiment, the coefficient of determination was 0.42; however, the $r^2$ values for the V8 irrigated and V10 dryland measurements were notably lower. The lack of strong relationships was surprising as N uptake and NDVI have been well correlated in other crops across several growth stages (Reeves et al., 1993; Stone et al., 1996; Sembiring et al., 2000). The inconsistency
observed in these data is possibly due to faulty equipment operation during data collection. While attempting to use the same sensor to collect similar data during the following wheat season, we discovered that it was not producing reliable measurements (due to a technical malfunction) and was subsequently replaced with an alternate sensor for data collection in the 2003 season of this study. Because it is unclear how the faulty sensor readings affected the data in 2002, relationships involving 2002 NDVI measurements will not be shown.

Measurements collected using the replacement sensor in 2003 showed considerably better correlation than the 2002 data ($r^2 = 0.49, p<0.0001$ [V6] and $r^2 = 0.48, p<0.0001$ [V8]; Figures 1.1a and 1.1b), supporting the hypothesis that the sensor was not operating correctly in 2002. Sembiring et al. (2000) reported high correlation ($r^2 = 0.39$ to $0.89$) between NDVI and N uptake for winter wheat in Oklahoma at different post-dormancy growth stages. They stressed that the differing slopes among stages necessitated calibration for specific growth stages and that a higher degree of variability in total N uptake was explained by NDVI as the growth stages advanced. Lukina et al. (2001) addressed these claims by pointing out that in the Sembiring et al. (2000) study, NDVI was calculated using an equation that did not take into account differences in incident light that would naturally be present when sensing at different times of the day, month, etc. Therefore, Lukina et al. (2001) used a modified NDVI equation and a sensor that measured both reflected and incident radiance to obtain NDVI values that were correlated ($r^2 = 0.75$) with N uptake over a number of different wheat growth stages. In irrigated corn, we found that using a sensor with a self-contained light source, which would result in corrected NDVI values similar to those obtained by Lukina et al. (2001), resulted in similar slopes but significantly different intercepts ($p<0.001$) when comparing measurements at V6 and V8 (Figures 1.1a and 1.1b). The lower intercept obtained with the V8 data is likely a result of an N dilution effect in the larger plants at that stage. Although our results agree with Sembiring et al. (2000) in that different growth stages can result in different regression equations, we did not observe an increase in $r^2$ values at the later growth stages, which is contradictory to the results reported by Sembiring et al. (2000). With the data presented in this study, it appears that growth stage-specific calibration will be necessary when correlating NDVI with N uptake in corn.
Relationship between NDVI and chlorophyll meter readings

Chlorophyll meter data collected in 2002 showed no significant correlation to NDVI; however, as in the case of NDVI measurements collected for correlation with N uptake in 2002, it is realistic to ascribe this lack of correlation to error in the collection of NDVI measurements due to technical malfunction of the sensor. Thus, 2002 data will not be reported.

Normalized difference vegetation index (NDVI) was significantly correlated with chlorophyll meter readings in 2003 ($r^2 = 0.45$, $p<0.0001$ [V6] and $r^2 = 0.48$, $p<0.0001$ [V8]; Figure 1.2). The relationship between the chlorophyll meter readings and NDVI is encouraging as several researchers have found chlorophyll meter readings useful for determining responsiveness of corn to sidedress N fertilizer applications (Wood et al., 1992; Varvel et al., 1997). The drawback to using chlorophyll meter readings to make decisions regarding N management is that they are not effective at determining specific N rates (Piekielek and Fox, 1992). Since NDVI measurements have been used successfully to determine in-season N rate recommendations for wheat in Virginia cropping systems (Phillips et al., 2004), these data indicate that the same potential may exist for corn. An added benefit to using NDVI to estimate SPAD readings is that unlike N uptake, the slopes (0.0034 and 0.0043) and intercepts (0.6435 and 0.5679) at the two vegetative growth stages were not different ($p<0.0001$); thus, a single equation can be used to relate NDVI to chlorophyll content across the two vegetative growth stages. This equation is reported in Figure 1.2.

Relationship between NDVI and plant physical characteristics

Normalized difference vegetation index (NDVI) determined at V6 and V8 were poorly correlated with plant height (Figure 1.3) and leaf width (data not shown). The results were a little surprising as other researchers have shown good correlation with plant physical characteristics including tiller density (Phillips et al., 2004) and leaf area index (Serrano et al., 2000) in winter wheat. Coefficients of determination were not improved when plotting NDVI against plant area, which was calculated as plant height*leaf width (data not shown). However, recent work in Oklahoma (Teal et al,
2004) has shown that, while in-season NDVI measurements are not well-correlated with corn biomass ($r^2 = 0.20$), a combination of plant height measurement and NDVI shows potential for predicting biomass ($r^2 = 0.83$). With corn biomass as a potential factor in predicting grain yield on a by-plant basis, their results suggest a strong need for further work to determine if corn physical characteristics are related to NDVI.

**Conclusions**

Normalized difference vegetation index (NDVI) was regressed against plant N uptake, chlorophyll content, plant height, leaf width, and plant area of field corn at various growth stages to determine if spectral reflectance could be useful as part of a non-destructive N management strategy for corn. Plant N uptake and NDVI were well correlated at both V6 ($r^2 = 0.49$) and V8 ($r^2 = 0.48$) in 2003 (Figures 1.1a and 1.1b).

Chlorophyll meter readings likewise were correlated ($r = 0.61$) with NDVI (Figure 1.2). Unlike the N uptake data, which had significantly different intercepts depending on growth stage (Figures 1.1a and 1.1b), the relationship between NDVI and chlorophyll content was not affected by growth stage between V6 and V8; thus a single equation could be used across the two growth stages to estimate chlorophyll content using NDVI (Figure 1.2). NDVI was poorly correlated with plant height (Figure 1.3), leaf width, and plant area (data not shown).

In the cases of N uptake and chlorophyll content, correlation with NDVI was not significantly improved at earlier or later growth stages (V6 vs. V8). From a practical standpoint, the V6 and V8 data are probably adequate for identifying the growth stages where most growers will be implementing in-season N management strategies; however, future work might need to focus on any differences in the established relationships that might occur as early as V4.

The relationships among NDVI, N uptake, and chlorophyll content established in this study support the use of NDVI as an indicator of plant N status and as a potential tool in developing N fertilization algorithms for corn in Virginia.
Table 1.1. Selected soil chemical properties† of Bojac sandy loam (coarse-loamy, mixed, semiaactive, thermic Typic Hapludult) soil at Eastern Shore AREC, Painter, VA.

<table>
<thead>
<tr>
<th>Year</th>
<th>pH</th>
<th>P</th>
<th>K</th>
<th>NH₄-N</th>
<th>NO₃-N</th>
<th>Organic C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>----mg kg⁻¹----</td>
<td>----kg ha⁻¹-----</td>
<td>g kg⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>6.00</td>
<td>112</td>
<td>101</td>
<td>33.73</td>
<td>12.73</td>
<td>4.9</td>
</tr>
<tr>
<td>2003</td>
<td>5.81</td>
<td>73</td>
<td>97</td>
<td>5.03</td>
<td>4.2</td>
<td>4.9</td>
</tr>
</tbody>
</table>

† pH; 1:1 soil to water ratio (Thomas, 1996)
P,K; extracted using Mehlich I double acid procedure (Kuo, 1996) and analyzed using ICP-EAS
NH₄-N, NO₃-N; 1:10 soil to water ratio, extracted using 2 M KCl, and colorimetrically determined using Bran+Luebbe Autoanalyzer
Table 1.2. Treatment structure of irrigated and dryland corn experiments in 2002 and 2003, Painter, VA.

<table>
<thead>
<tr>
<th>Trt</th>
<th>Preplant</th>
<th>Starter</th>
<th>Sidedress</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg N ha⁻¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1*</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>56</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
<td>112</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>168</td>
</tr>
<tr>
<td>5*</td>
<td>0</td>
<td>34</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>34</td>
<td>56</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>34</td>
<td>112</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>34</td>
<td>168</td>
</tr>
<tr>
<td>9*</td>
<td>0</td>
<td>56</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>56</td>
<td>56</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>56</td>
<td>112</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>56</td>
<td>168</td>
</tr>
<tr>
<td>13*</td>
<td>0</td>
<td>78</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>0</td>
<td>78</td>
<td>56</td>
</tr>
<tr>
<td>15</td>
<td>0</td>
<td>78</td>
<td>112</td>
</tr>
<tr>
<td>16</td>
<td>0</td>
<td>78</td>
<td>168</td>
</tr>
<tr>
<td>17*</td>
<td>67</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>18*</td>
<td>135</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>19*</td>
<td>202</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20*</td>
<td>269</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

* 6-row plots; all others 4-row plots
Figure 1.1a. Corn N uptake related to NDVI in irrigated plots at growth stage V6 (2003).

\[ y = 0.0026x + 0.7547 \]

\[ r^2 = 0.49 \]

\[ p < 0.0001 \]
Figure 1.1b. Corn N uptake related to NDVI in irrigated plots at growth stage V8 (2003).

\[ y = 0.0029x + 0.7008 \]

\[ r^2 = 0.48 \]

\[ p < 0.0001 \]
Figure 1.2. Corn chlorophyll meter readings correlated with NDVI in irrigated plots at growth stages V6 and V8 (2003). Third line represents the regression equation obtained when data are regressed without respect to growth stage.
Figure 1.3. Plant height (cm) correlated with NDVI of irrigated corn plants (2003).
Chapter 2: Use of NDVI to Estimate Yield and Determine Variable N Rates in Corn

Introduction

Optimizing N fertilizer use is becoming increasingly important from both an economic and environmental standpoint. Recognizing that variance in soil N availability is significant across areas of less than one square meter (Raun et al., 1998b; Solie et al., 1999), the conventional practice of applying a single rate of N fertilizer to several hectares once per growing season becomes unacceptable. In the search for more efficient ways of determining N fertilizer rates for optimum crop growth, optical sensor-based NDVI measurements have been given a primary focus in remote sensing as a tool that is indicative of plant N status without the need for destructive, time-consuming laboratory procedures.

The most successful work to utilize NDVI for this purpose has recently been accomplished in making in-season wheat grain yield predictions and subsequent N fertilization rates. The existing models for yield prediction (Lukina et al., 2001) and in-season N rate determination (Lukina et al, 2001; Raun et al., 2002; Mullen et al., 2003) in wheat are based on an index where NDVI measurements are divided by days from planting to sensing (DAP) and correlated with final grain yield ($r^2 = 0.64$; Lukina et al., 2001). This relationship can be used to make a yield potential estimate for crops of a future growing season. A restriction of the method defined by Lukina et al. (2001) is that the model was built using actual grain yields where no additional N was applied following the NDVI measurement; thus, any grain yield prediction made using this model assumes that the crop will receive no additional fertilization beyond what is required to merely sustain the existing yield potential. Raun et al. (2002) expanded the model by multiplying the number resulting from Lukina et al. (2001) (hereafter identified as $Y_{P0}$) by a response index (RI) (the average NDVI from a non-N-limiting section of the crop / the average NDVI from a crop area receiving the standard farmer N treatment) to predict the yield expected under further optimum N rate fertilization ($Y_{PN}$). Their data using an RI supported the idea that in-season calibration strips could not only indicate whether the
crop was expected to respond to additional N fertilization, but by how much grain yield could be increased with added N fertilizer.

In Virginia, an alteration to the model presented by Raun et al. (2002) was developed that more accurately predicted wheat grain yields in the Mid-Atlantic region (Phillips et al., 2005). For their model, Phillips et al. (2005) created a new variable by multiplying the sensor-based NDVI measurement of the target plot by an RI that was calculated using the same method of Raun et al. (2002). The product of these numbers was then divided by DAP to create a yield prediction index value as in the standard methods of Lukina et al. (2001) and Raun et al. (2002). The modified index value served as the independent variable in the regression equation presented by Lukina et al. (2001). The main difference was that the method of Phillips et al. (2005) incorporated RI prior to making a yield prediction; thus the only yield estimate made was assuming optimum N fertilization (YPN2). Their adjustment allowed for consideration of the degree of response on a site-specific basis, rather than assuming that all areas of the field will respond to added N at the same rate. Optimum N fertilizer rate recommendations under both the YPN (Raun et al., 2002) and YPN2 (Phillips et al., 2005) models were derived according to Mullen et al. (2003), in which the estimated grain N uptake in YP0 (predicted grain yield without additional fertilization) was subtracted from estimated grain N uptake in optimally fertilized plots (YPN or YPN2, respectively). The calculated fertilizer rates were then divided by an efficiency factor that provided an estimate of NUE for each respective region.

Because of the success encountered using sensor-based fertilization technology to increase NUE without reducing grain yields (Raun et al., 2002; Phillips et al., 2005), it seems advantageous to extend its applicability to other major crops that likewise use high levels of N fertilizer over many hectares. For example, in Virginia, wheat is commonly part of a corn–wheat–soybean rotation. Approximately 123,400 hectares are devoted to corn production in Virginia, while only 68,800 hectares are devoted to wheat (USDA–VASS, 2002). Therefore, this technology must also be applicable in corn production rotations to make its implementation into Mid-Atlantic cropping systems economically feasible.
Objectives

The specific objectives of this study were: i) to evaluate existing strategies for wheat yield prediction as applied to corn yield prediction, ii) to evaluate the existing approach for determining optimal N fertilizer rates of wheat as applied to corn, and iii) to establish the scale at which this system is most effective.

Materials and Methods

One irrigated and one dryland field experiment with corn was established each spring in 2002 and 2003 at the Eastern Shore Agricultural Research and Extension Center in Painter, VA. The production system utilized conventional tillage methods on a Bojac sandy loam (coarse-loamy, mixed, semiactive, thermic Typic Hapludult) soil. All experiments used a randomized complete block design with three replications. Plots utilized 76-cm row spacing and consisted of either 4 or 6 rows. In 2002, plot length was 5.5 m, and in 2003, plot length was 4.6 m. Prior to planting, composite soil samples (0 to 15 cm) were taken from the experimental area and nutrients other than N were applied according to soil test recommendations (Donohue and Heckendorn, 1994). Preplant incorporated ammonium nitrate fertilizer (34-0-0) was applied with a conventional drop-type spreader at rates 0, 67, 135, 202, and 269 kg N ha\(^{-1}\). Planting occurred on 02 May 2002 and 05 May 2003 using Pioneer brand hybrids 31G20 in 2002 and 32R25 in 2003 at seeding rates of 69,136 kernels ha\(^{-1}\) in the irrigated experiments and 54,321 kernels ha\(^{-1}\) in the dryland experiments. Starter N fertilizer was applied at planting at rates of 0, 34, 56, and 78 kg N ha\(^{-1}\) as 30 % urea ammonium nitrate (UAN) solution. Sidedress N fertilizer was applied at growth stage V8 (Ritchie et al., 1993), using 30% UAN solution at 0, 56, 112, and 168 kg N ha\(^{-1}\). This was accomplished using a Hagie high-clearance sprayer equipped with drop-tube nozzles that were spaced 76.2 cm apart and sprayed both sides of the plants at the base, 2 rows at a time. Irrigation was applied as needed, using a lateral-movement overhead sprinkler.

Normalized difference vegetation index [NDVI; using red (671 ± 6 nm) and near infrared (780 ± 6 nm) wavelengths] measurements were collected from the plant canopy using a hand-held GreenSeeker\textsuperscript{®} sensor (NTech Industries, Inc., Ukiah, CA). The sensor was centered over a row of plants and held approximately 0.9 m above the canopy while
being moved along the row to record measurements. Measurements were taken from rows to be harvested for grain (center two rows in each plot) in 2002 on dryland plots at V8 and V10, on irrigated plots at V8, and in 2003 on irrigated plots at V4, V6, and V8. NDVI measurements were also taken at V6 and V8 on each of 170 individual plants that had received 0, 34, 56, or 78 kg starter N ha\(^{-1}\) in the irrigated study.

Following the V8 NDVI measurements in 2003, independent fertilizer rates were calculated for 170 individual plants and applied on a by-plant basis. Fertilizer N rates were determined using modified versions of the sensor-based yield prediction models of Raun et al. (2002) and Phillips et al. (2005). Because these models were based on wheat yields, a calibration curve specific to corn was needed. A curve was constructed using NDVI and grain yield data collected from this study in 2002, Oklahoma (W.R. Raun, unpublished), Nebraska (J.S. Schepers, unpublished), and Mexico (I. Ortiz-Monasterio, unpublished). Once yield predictions were made for the individual plants, N rates were determined as described in Mullen et al. (2003) assuming corn grain N content was 1.25 % (PPI, 2004) and NUE at the study site was 60%. Nitrogen use efficiency can vary by site, depending on factors that potentially contribute to N loss. A reasonable range for NUE would be 33 to 88% (Lukina, 2001), but the value used for each site must be decided by the grower. Experience in Virginia suggested that at this site, 60% was a reasonable estimate of NUE. Thirty percent UAN fertilizer was applied at V8 by hand on a by-plant basis using a 5-mL graduated syringe. Fertilizer was surface band-applied approximately 5 cm from the base of the plant on both sides of the target plant extending half the distance to each neighboring plant in the row.

Grain was harvested from the center two rows in each plot on 19 September 2002 and 17 September 2003, using a conventional plot combine. Individual plants were harvested by hand on 17 September 2003. Following harvest, grain weight and moisture content data were recorded. Data were analyzed using linear regression (PROC REG) to correlate grain yield and NDVI data and PROC GLM Duncan’s multiple range test to compare treatment means (SAS Institute, Version 8.02).
Results and Discussion

Construction of grain yield prediction models

Data from 2002 NDVI and grain yield measurements were used to build models that the 2003 data would verify. The relationship between the standard yield prediction index (NDVI/DAP; Lukina et al., 2001) at growth stages V8 and V10 and grain yield of plots that received no N following sensing are shown in Figure 2.1. Both V8 dryland and V10 dryland data resulted in well correlated relationships ($r^2 = 0.55$ and 0.62, respectively). Growth stage V8 irrigated data were also well correlated ($r^2 = 0.71$), but consisted of fewer points than the dryland data. Plots in the irrigated study which received less than 78 kg N ha$^{-1}$ starter fertilizer had high index values at V8, which resulted in a much higher predicted yield than was actually obtained relative to other plots that received higher preplant or starter N rates. The yield prediction models were built on the assumption that soil N at the time of sensing was adequate to sustain plant health and growth rate throughout the remainder of the growing season until harvest. The low starter N rates combined with the elimination of water stress are reasons to assume that conditions in these plots were insufficient to maintain the plants’ need for N throughout the season following the V8 growth stage. Therefore, data from these plots were determined to be unsuitable for use in building a yield prediction model and subsequently removed. The remaining data points were combined with data from studies in Oklahoma, Mexico, and Nebraska to form a more comprehensive irrigated model for prediction of corn grain yields at V8 (Virginia data shown in Figure 2.1; unpublished data from outside Virginia not included).

Evaluation of grain yield prediction models – dryland corn

Estimates of grain yield with no sidedress N fertilizer (YP$_0$) were accurate predictors of actual yield (AY) in 75% of the starter treatments for the dryland study in 2003 (Table 2.1). The equation from which it is derived should therefore be applicable as a basis for making further predictions of yield with additional N. Yields predicted under optimum additional N fertilization using the method of Raun et al. (2002; YP$_N$) did not differ from the yields predicted without further N (YP$_0$; Table 2.1). This indicates that
the response index (RI) approximated a value of 1 for all treatments (N was not limiting) and so YP_N did not predict corn growth to be very responsive to additional N fertilizer. It is clear from the actual grain yields reported in Table 2.1 (AY) that this was a responsive site with regard to sidedress applied N fertilizer; thus the YP_N model (Raun et al., 2002) was ineffective at predicting grain yield response to additional N fertilizer. This was also found to be the case for winter wheat grown in the Mid-Atlantic (Phillips and Alley, 2000).

Yields predicted under optimum additional N fertilization, using the regionally-modified model, (YP_N2; Phillips et al., 2005) were higher than those predicted using YP_N, but still considerably lower than the actual yields obtained (Table 2.1). A potential explanation for this difference is that 2002 was a very dry growing season (21% below normal rainfall), and that this may have had an effect on the calibration model used to make the yield predictions in 2003 (Figure 2.1). The plants in 2003 had similar index values (NDVI/DAP) to those in 2002, but water stress present in 2002 during the critical period for plant uptake (Hanway, 1963) followed the V8 NDVI readings and resulted in low yields. Therefore, when similar index values for 2003 were applied to the 2002 model, the predicted yields obtainable with optimum fertilization were under predicted using both models (Table 2.1).

During 2003, the only treatments receiving sidedress N in which grain yields were accurately predicted by YP_N2 were those that received lower N rates, such as 56 kg N ha⁻¹ applied at sidedress following 0 or 34 kg N ha⁻¹ starter fertilizer (Table 2.1). Considering the yield response across sidedress N rates (AY; Table 2.1), it is clear that yields obtained using 56 kg N ha⁻¹ sidedress following 0 or 34 kg N ha⁻¹ starter fertilizer, although accurately predicted using the YP_N2 model, were N limited and were clearly not the true yield potentials of these plots.

**Evaluation of grain yield prediction models – irrigated corn**

In the 2003 irrigated study, YP₀ accurately predicted grain yield only for those plots receiving 0 or 78 kg N ha⁻¹ starter fertilizer, while over predicting final grain yield when 34 or 56 kg N ha⁻¹ starter was applied (Table 2.2). This result was interesting considering the increased accuracy of YP_N and YP_N2 (Table 2.2) compared to the dryland
study where $\text{YP}_0$ was accurate and $\text{YP}_N$ and $\text{YP}_{N2}$ were not (Table 2.1). A possible explanation is that heavy rainfall in the 2003 growing season (31% greater than normal) resulted in leaching of some of the starter-applied N. The explanation of the data would be that 1) $\text{YP}_0$ for plots receiving no starter was accurate because they were already N limiting, 2) the estimate for plots receiving 78 kg N ha$^{-1}$ was accurate because the starter rate was high enough to sustain yield but did not support uptake necessary to increase yield later in the season (which might have happened in the dryland study when $\text{YP}_0$ underestimated final grain yield following 78 kg ha$^{-1}$ starter N; Table 2.1), and 3) the N required to sustain the predicted yields following 34 and 56 kg N ha$^{-1}$ starter rates leached, resulting in over predictions of final grain yield.

Unlike the dryland models, both $\text{YP}_N$ and $\text{YP}_{N2}$ predicted a responsiveness of this site to additional N applications. What is interesting about the predicted responsiveness is that actual yields (AY) for all plots receiving 56 kg sidedress N ha$^{-1}$ either equaled or were less than their respective $\text{YP}_0$ values, indicating minimal response to applications of 56 kg N ha$^{-1}$ (Table 2.2). This supports our hypothesis that leaching might have occurred during in the growing season. In considering accuracy of the models at the 112 and 168-kg sidedress N ha$^{-1}$ rates, actual yield (AY) was predicted by $\text{YP}_N$ and over predicted by $\text{YP}_{N2}$ at the 0, 34, and 56-kg starter N ha$^{-1}$ rates (Table 2.2). While in plots receiving 78 kg starter N ha$^{-1}$, $\text{YP}_{N2}$ accurately predicted AY and $\text{YP}_N$ under predicted AY. The separation of methods as yield potentials increased might be a result of pooling data from different regions (VA, OK, NE, and MX).

Although efforts were made to select data that would be representative of yield potentials for Virginia, differences in growth stages, cropping systems, hybrids, etc. might affect the position of the curve compared to if all data were collected at a single location. In the case of wheat, growth stage, variety, location, soil type, and cropping system had no effect on the sensor-based yield prediction calibration curve (Lukina et al., 2001). Phillips and Alley (2000) reported that including Virginia-based $\text{YP}_0$ calibration data in the model also did not change the relationship, confirming that in wheat, it is possible that multiple calibration curves will not be needed to implement sensor-based fertilization technology across regions. The results from this study indicate that this may...
not be the case with corn. Figure 2.2 illustrates the effect of growth stage on the yield prediction index.

Assuming growth stage does not affect the yield prediction index, the points from the three data sets in Figure 2.2 should be directly on top of each other since all sensor measurements were collected from the same plots. It would be expected that the numerator (NDVI) and the denominator (DAP) of the index would change proportionately without changing the index value or the predicted yield across various growth stages. The fact that this did not happen (Figure 2.2), suggests that N uptake as a function of time (which is basically what the index represents) changes more dramatically during the typical sidedress period in corn (V4 to V8) than in wheat (GS28 to GS32). This hypothesis is supported by the N uptake patterns of corn and wheat (Ritchie et al., 1997 and Alley et al., 1996, respectively). Further investigation is needed to confirm whether growth stage specific yield prediction models will be needed in corn.

**Optimum N rate determination**

Considering that both the YP_N (Raun et al., 2002) and the YP_N2 (Phillips et al., 2005) grain yield prediction models severely underestimated actual grain yield obtained in the 2003 dryland study (Table 2.1), it is reasonable to conclude that N rate recommendations resulting from the predicted yields would also be well below optimum. Thus, only N rate recommendation data from the irrigated study will be discussed. Grain yield increased with increasing sidedress N rate up to 112 kg N ha⁻¹ following 0, 56, or 78 kg starter N ha⁻¹, while grain yield following 34 kg starter N ha⁻¹ continued to increase up to 168 kg sidedress N ha⁻¹ (Table 2.2). Analysis of the quadratic yield responses following 0, 56, and 78 kg starter N ha⁻¹ indicated that the critical sidedress N rate for optimum yield was approximately 100 kg N ha⁻¹ (data not shown).

Nitrogen rate recommendations in Virginia are based on realistic yield goals for different production regions and indicate that 1 kg N should be applied for each 55 kg expected grain yield (Donohue and Heckendorn, 1994). A realistic yield goal for corn production at the study site is 9.4 Mg ha⁻¹; thus 170 kg N ha⁻¹ would be the recommended N rate. Considering the 56 and 78-kg N ha⁻¹ starter rates that resulted in optimum yields
equal to or greater than the 9.4-Mg ha\textsuperscript{-1} yield goal at the 112 kg N ha\textsuperscript{-1} sidedress rate (Table 2.2), the yield goal and recommended N rate appeared to be accurate.

The recommended N rates generated based on the sensor-based yield predictions were considerably lower than what were determined to be optimum N rates in this study (Table 2.3). This held true at all levels of starter N; for example, at 56 kg N ha\textsuperscript{-1} starter, the recommended rates using YP\textsubscript{N} and YP\textsubscript{N2} were 22 and 34 kg N ha\textsuperscript{-1}, respectively (Table 2.3). The difference in recommended N rates is a reflection of the difference in predicted grain yield response between the two methods (Table 2.2). It would appear from these data that while the two methods were accurate at predicting grain yield response to additional N fertilizer, the procedure used to calculate the N requirement necessary to achieve the increase in yield is inaccurate. It is important to consider, however, that a critical component in the N fertilization algorithm is an estimate of NUE.

The NUE estimate used in calculating the recommended N rates in the sensor-based systems was 60%. The actual NUE values obtained in this study, according to starter N rate, were 22% for 0 kg N and 34 kg N, 33% for 56 kg N, and 25% for 78 kg N (Table 2.3). These numbers were calculated using the following equation:

\[ \text{NUE} = \frac{(N \text{ removed in the treated plot} - N \text{ removed in the check plot})}{N \text{ applied}} \]

Percent N in the grain was assumed to be 1.25%. These efficiency values are extremely low considering that the worldwide estimate of NUE of cereal grains for developed countries is approximately 40% (Raun and Johnson, 1999). The heavy rainfall throughout the growing season of 2003 was probably a major contributor to the low NUE values observed in this study. What is interesting about the N rate recommendations generated using the yield prediction models is that if the YP\textsubscript{N2}-based rates (Table 2.3) would have been calculated using an NUE estimate of 26% (average NUE across all starter rates; Table 2.3) rather than 60%, the average recommendation across starter N rates would have been 102 kg N ha\textsuperscript{-1} instead of 44 kg N ha\textsuperscript{-1} and much closer to what was determined to be the optimum N rate in 2003. However, we believe 60% to be a reasonable NUE estimate for many of the Virginia corn-growing regions and that
lowering it to near what was observed in 2003 will most often result in unrealistically high N rate recommendations.

If we consider the current recommendation of 1 kg N per 55 kg expected grain yield, applying 112 kg N ha\(^{-1}\) should have resulted in grain yield increases of approximately 6.2 Mg ha\(^{-1}\) over yields obtained when no sidedress N was applied; however, no yield increases greater than 3.0 Mg ha\(^{-1}\) were observed (Table 2.3). According to the current recommendations (1 kg N per 55 kg expected grain yield), the yield increases observed should have been attainable with an average sidedress N application of 46 kg ha\(^{-1}\), which is not different from the 44-kg N ha\(^{-1}\) rate recommended using the YP\(_{N2}\) yield prediction model (Table 2.3).

**By-plant N fertilization**

Another important consideration to make when deciding what the NUE estimate will be in sensor-based fertilization algorithm is that the application will be made on a variable-rate basis at a very fine resolution (www.ntechindustries.com). The ability to apply variable rates of N fertilizer at scales as fine as a single plant in corn, allows us to reasonably conclude that NUE will be markedly higher compared to a fixed-rate application to an entire field. Sensor-based N fertilization work in wheat has assumed this value to be as high as 70% (Mullen et al., 2003). In our study, the recommended N rates calculated on a by-plant basis (assuming 60% NUE) averaged 66 kg N ha\(^{-1}\) across starter N rates and ranged from 43 to 85 kg N ha\(^{-1}\) (Table 2.4). Applying N on a by-plant basis significantly increased grain yield compared to applying the same average rate to the entire row at all levels of starter N (Table 2.4). This result is important in that it demonstrates not only the great spatial variability that is present within such a small area of a field, but also the need to sense and treat at this level to obtain maximum yields. Currently, the sensor work conducted using this algorithm in wheat studies has been utilizing resolutions ranging from 0.4 to 1.0 m\(^2\) in which readings are averaged across multiple plants (Lukina et al., 2001; Raun et al., 2002; Mullen et al., 2003; Phillips et al., 2005), but the results in Table 2.4 show the potential necessity of sensing and treating corn plants on an individual basis under these methods.
Another interesting observation regarding the by-plant data is that the yields obtained at an average rate of 66 kg N ha\(^{-1}\) were equal to or greater than those obtained using 112 kg N ha\(^{-1}\) in the whole plot study (Table 2.2). The reduction in N application rate at equivalent grain yield levels resulted in the YP\(_{N2}\)-based, by-plant, variable-rate fertilization strategy having an NUE of 57% averaged over starter N rates (data not reported). The increased efficiency is also evident when one considers that when the by-plant average N rate (66 kg N ha\(^{-1}\)) was applied as a fixed rate to the entire row, the yields obtained (Table 2.4) were equivalent to those obtained using 56 kg N ha\(^{-1}\) in the whole plot study (Table 2.2). These data also indicate that addressing spatial variability in grain yield potential is as great, if not of greater importance than identifying the absolute optimum N rate.

**Conclusions**

Existing strategies for wheat yield prediction were applied to both dryland and irrigated corn yield prediction. In the case of dryland corn (Table 2.1), grain yield estimates in field plots receiving no additional N fertilizer (YP\(_0\)) were mostly accurate. As previously determined for Mid-Atlantic wheat, the method of Raun et al. (2002) did not accurately predict corn yield response to additional N (YP\(_N\)) in the dryland study. The regionally-modified model (Phillips, 2005; YP\(_{N2}\)) also did not predict yield response accurately. A likely explanation of the inadequacies of these strategies lies in the fact that the 2002 model which was used to predict 2003 yields (Figure 2.1) was built using data from an extremely dry year and was applied to crops of an extremely wet year, resulting in severe under prediction. In the irrigated study (Table 2.2), YP\(_0\) was accurate in only half of the starter N rate treatments, likely as a result of N leaching. While YP\(_N\) and YP\(_{N2}\) both predicted responsiveness in this study, YP\(_N\) was accurate at 112 and 168 kg sidedress N ha\(^{-1}\) rates in treatments receiving 0, 34, and 56 kg starter N ha\(^{-1}\), while YP\(_{N2}\) was accurate at those sidedress rates in treatments receiving 78 kg starter N ha\(^{-1}\). This may be evidence that, contrary to what is suggested for wheat (Phillips and Alley, 2000), corn may require calibration curves specific to location. Corn may also require calibration curves specific to growth stage (Figure 2.2), but further research is needed in this area.
The existing approach for determining optimal N fertilizer rates for wheat (Mullen et al., 2003) was applied to corn, using values of 1.25% corn grain N content and 60% NUE. The critical sidedress N rate for optimum yield in this study was determined to be approximately 100 kg N ha\(^{-1}\). The N rate recommendations determined by the yield predictions were much lower than this optimum amount; however, the shortcoming of this method of determining N rate recommendations appears to lie in the fact that the actual NUE obtained during the 2003 season was between 22 and 33%, depending on starter N treatment, when the original estimate was 60%. However, 2003 was an unusually wet year, and so there seems to be no reason to alter the method for application in more typical years.

Sidedress N was applied on a by-plant basis, and demonstrated at all levels of starter N a significant increase in grain yield compared to applying the same average rate to the entire row (Table 2.4). In addition, by-plant fertilization showed increased NUE (57% averaged over starter N rates) compared with a single-rate application. This practice demonstrates the great spatial variability in grain yield potential that exists within a small area of a field and is strong evidence for the subsequent need to sense and treat at this level for maximum corn grain yields.

The results of this study suggest that the existing methods for sensor-based wheat yield predictions and optimum N rate determination may be additionally valid for corn in a more typical growing season than those experienced in 2002 and 2003, and that increased NUE and maximum yields are obtained when these methods are utilized at the plant-by-plant level.
Table 2.1. Dryland corn grain yields (AY) in 2003 compared to predicted yield without additional fertilizer ($Y_{P0}$), predicted yield with optimal additional fertilizer ($Y_{PN}$), and predicted yield with optimal fertilizer using an adaptation of $Y_{PN}$ suited to the Mid-Atlantic region ($Y_{PN2}$).

<table>
<thead>
<tr>
<th>Starter N</th>
<th>Sidedress N</th>
<th>$Y_{P0}$</th>
<th>$Y_{PN}$</th>
<th>$Y_{PN2}$</th>
<th>AY</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>3.2a*</td>
<td></td>
<td></td>
<td>3.1a</td>
</tr>
<tr>
<td>0</td>
<td>56</td>
<td>3.2b</td>
<td>3.6b</td>
<td>5.5a</td>
<td>5.3a</td>
</tr>
<tr>
<td>0</td>
<td>112</td>
<td>3.2c</td>
<td>3.6c</td>
<td>5.5b</td>
<td>7.3a</td>
</tr>
<tr>
<td>0</td>
<td>168</td>
<td>3.2c</td>
<td>3.6c</td>
<td>5.5b</td>
<td>7.3a</td>
</tr>
<tr>
<td>34</td>
<td>0</td>
<td>3.7a</td>
<td></td>
<td></td>
<td>4.0a</td>
</tr>
<tr>
<td>34</td>
<td>56</td>
<td>3.7b</td>
<td>4.0b</td>
<td>5.7a</td>
<td>5.8a</td>
</tr>
<tr>
<td>34</td>
<td>112</td>
<td>3.7b</td>
<td>4.0b</td>
<td>5.7a</td>
<td>6.5a</td>
</tr>
<tr>
<td>34</td>
<td>168</td>
<td>3.7c</td>
<td>4.0c</td>
<td>5.7b</td>
<td>7.0a</td>
</tr>
<tr>
<td>56</td>
<td>0</td>
<td>4.1a</td>
<td></td>
<td></td>
<td>5.2a</td>
</tr>
<tr>
<td>56</td>
<td>56</td>
<td>4.1c</td>
<td>4.3c</td>
<td>5.4b</td>
<td>6.3a</td>
</tr>
<tr>
<td>56</td>
<td>112</td>
<td>4.1c</td>
<td>4.3c</td>
<td>5.4b</td>
<td>7.2a</td>
</tr>
<tr>
<td>56</td>
<td>168</td>
<td>4.1c</td>
<td>4.3c</td>
<td>5.4b</td>
<td>6.3a</td>
</tr>
<tr>
<td>78</td>
<td>0</td>
<td>4.5b</td>
<td></td>
<td></td>
<td>5.7a</td>
</tr>
<tr>
<td>78</td>
<td>56</td>
<td>4.5b</td>
<td>4.6b</td>
<td>5.6a</td>
<td>6.3a</td>
</tr>
<tr>
<td>78</td>
<td>112</td>
<td>4.5c</td>
<td>4.6c</td>
<td>5.6b</td>
<td>7.3a</td>
</tr>
<tr>
<td>78</td>
<td>168</td>
<td>4.5c</td>
<td>4.6c</td>
<td>5.6b</td>
<td>8.1a</td>
</tr>
</tbody>
</table>

* Values having the same letter within treatment are not statistically different at the 0.05 probability level. $Y_{P0}$, Lukina et al., 2001; $Y_{PN}$, Raun et al., 2002; $Y_{PN2}$, Phillips et al., 2005
Table 2.2. Irrigated corn grain yields (AY) in 2003 compared to predicted yield without additional fertilizer (YP$_0$), predicted yield with optimal additional fertilizer (YP$_N$), and predicted yield with optimal fertilizer using an adaptation of YP$_N$ suited to the Mid-Atlantic region (YP$_{N2}$).

<table>
<thead>
<tr>
<th>Starter N</th>
<th>Sidedress N</th>
<th>YP$_0$</th>
<th>YP$_N$</th>
<th>YP$_{N2}$</th>
<th>AY</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>7.5a*</td>
<td>6.8a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>0</td>
<td>7.6a</td>
<td>6.3b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>56</td>
<td>0</td>
<td>8.0a</td>
<td>6.6b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>78</td>
<td>0</td>
<td>8.4a</td>
<td>7.7a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>56</td>
<td>7.5c</td>
<td>8.8b</td>
<td>10.0a</td>
<td>6.7c</td>
</tr>
<tr>
<td>0</td>
<td>112</td>
<td>7.5c</td>
<td>8.8b</td>
<td>10.0a</td>
<td>8.8b</td>
</tr>
<tr>
<td>0</td>
<td>168</td>
<td>7.5c</td>
<td>8.8b</td>
<td>10.0a</td>
<td>8.4b</td>
</tr>
<tr>
<td>34</td>
<td>56</td>
<td>7.6c</td>
<td>8.8b</td>
<td>10.0a</td>
<td>6.6d</td>
</tr>
<tr>
<td>34</td>
<td>112</td>
<td>7.6c</td>
<td>8.8b</td>
<td>10.0a</td>
<td>8.2bc</td>
</tr>
<tr>
<td>34</td>
<td>168</td>
<td>7.6c</td>
<td>8.8b</td>
<td>10.0a</td>
<td>9.3b</td>
</tr>
<tr>
<td>56</td>
<td>56</td>
<td>8.0c</td>
<td>9.0b</td>
<td>10.1a</td>
<td>7.2d</td>
</tr>
<tr>
<td>56</td>
<td>112</td>
<td>8.0b</td>
<td>9.0b</td>
<td>10.1a</td>
<td>9.6a</td>
</tr>
<tr>
<td>56</td>
<td>168</td>
<td>8.0c</td>
<td>9.0b</td>
<td>10.1a</td>
<td>9.1b</td>
</tr>
<tr>
<td>78</td>
<td>56</td>
<td>8.4c</td>
<td>9.2b</td>
<td>10.3a</td>
<td>7.9c</td>
</tr>
<tr>
<td>78</td>
<td>112</td>
<td>8.4c</td>
<td>9.2b</td>
<td>10.3a</td>
<td>9.9a</td>
</tr>
<tr>
<td>78</td>
<td>168</td>
<td>8.4c</td>
<td>9.2b</td>
<td>10.3a</td>
<td>9.6ab</td>
</tr>
</tbody>
</table>

* Values having the same letter within treatment are not statistically different at the 0.05 probability level
YP$_0$, Lukina et al., 2001; YP$_N$, Raun et al., 2002; YP$_{N2}$, Phillips et al., 2005
Table 2.3. Recommended N rate (RNR) for 2003 irrigated corn as calculated using \( YP_N \) (predicted yield with optimum additional fertilizer) and \( YP_{N2} \) (predicted yield with optimum additional fertilizer as adapted to Mid-Atlantic region). Actual grain yields obtained under varying starter N treatments with no additional N applied (No N) or with optimal N rates (+N†) applied, in addition to resultant nitrogen use efficiency (NUE), are also shown.

<table>
<thead>
<tr>
<th>Grain Yield</th>
<th>Starter N</th>
<th>No N</th>
<th>+N†</th>
<th>NUE</th>
<th>RNR ( YP_N )</th>
<th>RNR ( YP_{N2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>6.8</td>
<td>8.8</td>
<td>22</td>
<td>27</td>
<td>52</td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>6.3</td>
<td>9.3</td>
<td>22</td>
<td>25</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>56</td>
<td>6.6</td>
<td>9.6</td>
<td>33</td>
<td>22</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>78</td>
<td>7.7</td>
<td>9.9</td>
<td>25</td>
<td>16</td>
<td>40</td>
<td></td>
</tr>
</tbody>
</table>

†Optimum sidedress N rate

RNR, variation on Mullen et al., 2003 using 1.25% grain N and 60% NUE
Table 2.4. Recommended N rate (RNR) for 2003 irrigated corn as calculated using YP_{N2} (predicted yield with optimum additional fertilizer as adapted to Mid-Atlantic region) and range of rates actually applied to individual plants receiving varying levels of starter N fertilizer. Also shown are actual grain yields when plants were fertilized on a by-plant basis or according to a fixed rate for multiple plants.

<table>
<thead>
<tr>
<th>Starter N</th>
<th>RNR YP_{N2}</th>
<th>Range</th>
<th>Grain Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg ha^{-1}</td>
<td>Mg ha^{-1}</td>
<td>By-plant</td>
</tr>
<tr>
<td>0</td>
<td>62</td>
<td>43-85</td>
<td>9.6</td>
</tr>
<tr>
<td>34</td>
<td>62</td>
<td>43-72</td>
<td>8.3</td>
</tr>
<tr>
<td>56</td>
<td>67</td>
<td>43-72</td>
<td>10.8</td>
</tr>
<tr>
<td>78</td>
<td>71</td>
<td>57-85</td>
<td>10.8</td>
</tr>
</tbody>
</table>

RNR, variation on Mullen et al., 2003 using 1.25% grain N and 60% NUE
Figure 2.1. Relationships between 2002 corn grain yield and NDVI measurements at growth stages V8 and V10 divided by days after planting (DAP).

- V8 Dryland  $y = 43.794e^{312.04x}$  $r^2 = 0.55$
- V8 Irrigated  $y = 1247.9e^{114.37x}$  $r^2 = 0.71$
- V10 Dryland  $y = 16.455e^{433.23x}$  $r^2 = 0.62$
Figure 2.2. Relationships between 2003 corn grain yields and NDVI measurements at growth stages V4, V6 and V8 divided by days after planting (DAP).
Chapter 3: Summary and Conclusions

Correlation of NDVI with chlorophyll meter readings, tissue N content, and plant physical characteristics in corn was conducted in 2002 and 2003 to verify NDVI sensor readings as a valid method of indicating plant N status at various growth stages in corn. A technical malfunction in the sensor during the 2002 season made much of the collected NDVI data unusable in this context. However, plant N uptake and NDVI were well correlated at V6 and V8 in 2003, as were chlorophyll meter readings and NDVI. It was interesting to observe that the relationship between chlorophyll meter readings and NDVI, unlike plant N uptake and NDVI, was not affected by growth stage between V6 and V8, making a single equation useful across these stages. NDVI was poorly correlated with plant height, leaf width, and plant area as estimated in this study. While V6 and V8 represent stages at which growers will make in-season management decisions, it is suggested that further research be conducted to evaluate the correlations at an earlier growth stage such as V4. The strong correlations among NDVI and plant N uptake and chlorophyll meter readings at V6 and V8 recommend the use of NDVI as a tool for in-season N management in Virginia corn.

The validity of sensor-based variable-rate N fertilization strategies in wheat as applied to corn was difficult to determine, based on the fact that data from each year represented two contrasting, unusual extremes in rainfall for the area. While the predicted yield of corn receiving no additional N fertilization (YP₀) was accurate in the dryland study, both YPₙ and YPₙ₂ methods under predicted yield response to additional sidedress N fertilization at all starter N rates. In the irrigated study, leaching resulted in under prediction of YP₀ in half of the starter N rate treatments. Both models (YPₙ and YPₙ₂) predicted responsiveness, but accuracy varied between the methods, suggesting the need for calibration curves specific to location and possibly growth stage. The existent approach for determining in-season N rates for wheat showed promise for use in corn, but recommendations were less than optimum as a result of underestimating NUE for the 2003 season. This result underscores the importance of the NUE factor in this method, but should not be a concern for alteration in a more typical year. Analyzing corn on a by-
plant basis showed that spatial variability in small areas of the field is a major consideration when optimizing fertilizer N use. Both grain yield and nitrogen use efficiency were greatly improved when sensing and treating individual plants compared to sensing and treating a row of plants with an average N rate, and therefore strongly recommends this technique for future N management strategy implementation.

Sensor-based variable rate N management has potential for use in corn production in Virginia and may be accomplished by further analysis of the existing wheat yield prediction models and nitrogen fertilization optimization algorithms in other production regions of Virginia.
References


Vita

Emily Kathryn Lewis
Crop and Soil Environmental Sciences
Virginia Polytechnic Institute and State University
Blacksburg, VA 24060
emilykl@vt.edu

Education

Presentations

Professional Memberships

Honors
Graduate Research Assistantship, Virginia Polytechnic Institute and State University
Full-Tuition Two-Term Continuing Student Scholarship, Brigham Young University
Full-Tuition Two-Semester Transfer Student Scholarship, Brigham Young University
Academic/Leadership Scholarship, Southern Virginia College
Young Womanhood Recognition Award, The Church of Jesus Christ of Latter-day Saints