Nitrogen stress sensing and in-season application for corn production

by

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This is to certify that the master's thesis of

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Signatures have been redacted for privacy

TO:

My wonderful and supportive family

And the love of my life,

Brent.

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General Introduction

Determining the appropriate N application rate for corn (*Zea mays* L.) production, as well as timing of N application, are some of the more difficult challenges facing producers today. Nitrogen fertilization is a key component to corn production. Past N application practices and a desire for high yields, fueled by low fertilizer N costs, have led producers to over-apply N rather than falling short of crop N needs and risk costly yield losses. Due to increased environmental concerns, the susceptibility for nitrate leaching to ground water, loss in tile lines, and the rising costs of fertilizer N, producers are looking at management strategies that have the potential to improve N use efficiency and economic return.

Technological developments have outpaced agronomic nutrient management research with equipment such as handheld and on-the-go sensors for detecting N stress in corn, along with high clearance equipment designed to travel through tall corn for in-season application. Knowledge of how best to use these devices for N input decisions has been slow in catching up with the optical and mechanical advances. Many sensing approaches and tools are available that aim to refine N management. However, there exists a need for predictive relationships between information provided by these tools and expected N application need.

The Minolta SPAD 502 chlorophyll meter (CM) is a handheld device that measures transmittance of light through a leaf at 650 and 940 nm. It is used to detect N stress in corn plants by measuring leaf greenness. It was been well documented that CM readings are significantly related to the N status of corn plants (Blackmer and Schepers, 1994; Piekielek and Fox, 1992; Piekielek et al., 1995; Schepers et al., 1992a; Wood et al., 1992). This relationship is similar to corn grain yield response to N rate in that it is curvilinear and reaches a plateau at high leaf N levels (Blackmer and Schepers, 1994; Wood et al., 1992).

This plateau indicates that the CM readings are not sensitive to excess plant available N. The unitless reading that the CM provides has been found to be useful for determining plant N status when factors other than plant N status are constant; but these readings can be affected by other factors that affect leaf color, such as drought and hybrid. Chlorophyll meter readings, in field settings where all factors cannot be controlled, are most useful when compared to an adequately fertilized or non-N limited reference within the same field, creating a normalized relative CM (RCM) value or sufficiency index (SI) (Schepers et al., 1992a; 1992b; Schepers, 1994). According to the SI, when the RCM value drops below 95% of readings from the reference, N deficiency stress has occurred (Blackmer and Schepers, 1995; Varvel et al., 1997).

Timing for corn plant N status determination is important in relation to synchronization of soil N availability, N application, crop N demand, and development of N stress. According to Dwyer et al. (1991), the narrow range of CM readings measured at the V6 growth stage makes it difficult to separate N-deficient from N-sufficient field areas. Varvel et al. (1997) found that severe but not slight N deficiencies could be detected using the CM at the V8 stage. Binder et al. (2000), however, documented a 12% reduction in grain yield when N application was postponed beyond the V6 growth stage and little or no N was applied prior to sensing. Also less than 20% of the total N uptake by corn occurs prior to V8 Schepers et al. (1995). Russelle et al. (1983) points out that the rate of N uptake by corn is affected by weather, planting date, and time of fertilizer application, but is generally greatest between V8 and R1 stages.

One approach to better matching N application rate to crop N need is a split application, focusing the split component of the application at mid-to-late vegetative corn growth stages (in-season N). In-season refers to application of fertilizer during the growing season, but later than the traditional early sidedress application timing. Applying N sidedress is an effective practice on coarse-textured soils, and multiple applications are easily implemented when fertigation is practiced. On medium to fine textured soils in rain-fed corn production areas, research has indicated that split applications of fertilizer N are often equal to preplant N, but can sometimes be more effective than an all preplant application (Bundy, 1986; Randall and Schmitt, 1994; Killorn et al., 1995; White and Gress, 2002). The benefit of an in-season strategy includes not only applying N when the corn plant needs and is rapidly utilizing N, but also it provides an opportunity to better match N application with crop fertilization requirements. Many methods have been investigated for assisting in determination of optimal N application rates, such as soil nitrate testing. A more recently investigated approach is corn plant N stress sensing.

Several studies have estimated N application rate using RCM values, but with limited success. Blackmer and Schepers (1995) demonstrated that fertigation soon after CM detection of a significant N stress (SI below 95%) could maintain an adequate crop N status, preventing yield losses. This technique requires constant monitoring of the corn crop with the CM and a relatively small application rate each time N stress is detected. While this approach proved successful in irrigated corn production, regular monitoring is time intensive and the sensing indicated N deficiencies but not the total amount of fertilizer N needed to be applied for the entire season. Francis and Piekielek (1999) provided an alternative management plan for in-season N rate determination. This involved a modified mass balance calculation approach that takes into account several factors in addition to plant N stress sensing (corn yield goals, rotation and manure credits, and stage of crop development). However, N application rate based on corn yield goals has been found to be poorly correlated with optimum N rates (Doerge, 2002). In addition, proper crediting of N from animal wastes is difficult (Bausch and Diker, 2001). This approach also did not directly determine, from plant N stress sensing, how much N to apply. There still exists a need for an effective N rate determination method in rain-fed corn production where in-season N application would be limited to one application.

The objectives of these papers were to one, identify a calibration for relating RCM values to N fertilization rate for estimating in-season applications in rain-fed corn production; and two, test the effectiveness of in-season N management strategies through corn plant N stress sensing and in-season adjusted N fertilizer applications with Iowa growing conditions.

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Thesis Organization

This thesis is organized with a general introduction, two papers that will be submitted to *Agronomy Journal*, and an overall summary. Each individual paper has an abstract, introduction, materials and methods, results and discussion, and summary.

Using Relative Chlorophyll Meter Values to Determine N Application Rates for Corn

A paper to be submitted to Agronomy Journal

J. A. Hawkins, J. E. Sawyer, D. W. Barker, and J. P. Lundvall

Abstract

Determining the most economical N application rate is one of the more difficult challenges facing producers. Since N is a large input cost for corn (*Zea mays* L.) production, and fertilizer N costs are increasing dramatically, producers are looking for methods to improve N rate management. Crop sensing tools designed to measure plant N stress are available to producers. However, there exists a need for a calibrated relationship between information delivered from these tools and expected N rate application need. Nitrogen rate trials were conducted across Iowa in 1999-2005 with corn following soybean (*Glycine max* L. Merr.) and continuous corn. Multiple rates of N were applied preplant or early sidedress, with in-season corn plant N stress sensing at the R1 growth stage with the Minolta SPAD 502 chlorophyll meter (CM). Results show a significant quadratic-plateau relationship between relative chlorophyll meter (RCM) values and differential from economic optimum N rate (EONR) ($R^2 = 0.73, p < 0.001$) for corn following soybean. The regression fit has a RCM value of 0.97 at zero differential from economic optimum N rate. Continuous corn has a similar relationship between RCM and ND ($R^2 = 0.76, p < 0.001$) indicating the same calibration for N application rate based on RCM can be used for both rotations. Evaluation of RCM values collected at multiple corn growth stages indicated similar RCM values at the V15 and R1 growth stages, but larger RCM values at V8 and smaller values at R3 at the same N rates. The similarity in RCM values at V15 and R1 suggest that there is a period of time during late vegetative growth, rather than one critical time, to collect CM readings. Earlier (V15) CM sensing of plant N stress should provide adequate time for making in-season N rate decisions and applications before R1 growth stage. The calibration for N application rate based on RCM developed from this research could be used by producers to determine additional N need in-season for corn production.

Abbreviations: CM, chlorophyll meter; RCM, relative chlorophyll meter; EONR, economic optimum N rate; ND, N rate differential from EONR.

Introduction

Determining the most economic N application rate is one of the more difficult challenges facing producers today. Since N is a large nutrient input for corn production, and nitrate is highly susceptibility to movement and loss from soils, Iowa's surface and groundwater are vulnerable to water quality impairment. With rising costs of fertilizer N and the likelihood for more stringent regulations governing agricultural nutrient inputs, producers are looking to improve their N management decisions. Technological developments have outpaced agronomic nutrient management research with equipment such as handheld and on-the-go sensors for detecting N stress in corn, along with high clearance equipment designed to travel through tall corn for in-season application. Knowledge of how best to use these devices for N input decisions has been slow in catching up with the optical and mechanical advances.

The Minolta SPAD 502 CM is a handheld device that measures transmittance of light through a plant leaf at 650 and 940 nm. The first wavelength coincides with the spectrum region associated with maximum chlorophyll activity, while the second provides internal calibration to the instrument; compensating for leaf thickness, water status, and other plant factors. This portable device is used to measure leaf greenness simply by clamping it onto a leaf. It was been well documented that CM readings are significantly related to the N status of corn plants (Blackmer and Schepers, 1994; Piekielek and Fox, 1992; Piekielek et al., 1995; Schepers et al., 1992a; Wood et al., 1992). This relationship is similar to corn grain yield response to N rate in that it is curvilinear and reaches a plateau at high leaf N concentrations (Blackmer and Schepers, 1994; Wood et al., 1992). This plateau indicates that the CM readings are not sensitive to excess plant available N and luxury consumption. The unitless reading that the CM provides has been found to be useful for determining plant N status when all factors other than N are constant; however CM readings can be affected by several factors that affect leaf color, such as drought and hybrid. Chlorophyll meter readings, in field settings where all factors cannot be controlled, are most useful when compared to an adequately fertilized or non-N limited reference within the same field, creating a normalized relative CM (RCM) value or sufficiency index (SI) (Schepers et al., 1992a; 1992b; Schepers, 1994). According to the SI, when the RCM value drops below 95% of readings from the reference, N deficiency stress has occurred (Blackmer and Schepers, 1995; Varvel et al., 1997).

Fox et al. (2001) found that RCM values were 92% accurate in determining corn N status. This is approximately the same level of accuracy as the late season stalk nitrate test. The advantages the CM has over the stalk nitrate test are that it is easy to use, quick, provides instantaneous results, and can be used to monitor the N status earlier and several times during the growing season. Since leaf greenness can be influenced by hybrid, stage of growth, and other nutrients, the within field non-N limited reference approach reduces variability in N stress sensing between fields, thus allowing improved detection of coloration stress that is due to N shortage.

Timing for corn plant N status determination is important in relation to synchronization of soil N availability, N application, crop N demand, and development of N stress. According to Dwyer et al. (1991), the narrow range of CM readings measured at the V6 growth stage makes it difficult to separate N-deficient from N-sufficient field areas. Varvel et al. (1997) found that severe but not slight N deficiencies could be detected using the CM at the V8 stage. Binder et al. (2000), however, documented a 12% reduction in grain yield when N application was postponed beyond the V6 growth stage and little or no N was applied prior to sensing. Less than 20% of the total N uptake by corn occurs prior to V8 (Schepers et al., 1995). Russelle et al. (1983) points out that the rate of N uptake by corn is affected by weather, planting date, and time of fertilizer application, but is generally greatest between V8 and R1 growth stages.

Nitrogen deficiencies detected late in the growing season (R4 to R5) are more highly correlated with yield response to N than early season N stress detection (Blackmer and Schepers, 1995). Russelle et al. (1983) also found that when N applications were delayed to V16, the time of greatest N uptake was generally delayed until after R1.Sch arf et al. (2002) found that when N application to corn was delayed until V12 or V16 there was a small but significant yield reduction. A greater reduction in yield resulted when application was delayed until R1; however, yield was still highly responsive to N applied at this stage.

In general, the cutoff period to avoid substantial yield loss with in-season N applications appears to be before the VT to R1 growth stages (Russelle et al., 1983; Binder et al., 2000). Potential for yield reduction with late N application is also related to the amount of soil or fertilizer N available before N stress sensing occurs. When using the CM approach for monitoring the N status of corn, decisions on total crop N need should be more accurate when made later in the season and after significant N uptake. Although N stress sensing during reproductive growth stages in corn provides a more accurate determination of total crop N need, N uptake and yield recovery this late in the season has not been successful. The window for sensing and in-season N application becomes narrow with mid-to-late vegetative growth stage timing, but it is this timing that researchers and producers are trying to make feasible for corn production.

Several researchers have tried to estimate N application rate using RCM readings, with limited success. Blackmer and Schepers (1995) demonstrated that fertigation soon after CM detection of a significant N stress (SI below 95%) could maintain an adequate crop N status, preventing yield losses. This technique requires constant monitoring of the corn crop with the CM and a small application rate each time N stress is detected. While this approach proved successful in irrigated corn production, regular monitoring is time intensive, and the sensing approach indicated N deficiency but not the total amount of fertilizer N needed to be applied for the entire season. Francis and Piekielek (1999) provided an alternative management plan for in-season N rate determination. This involved a calculation approach that takes into account several factors, including plant N stress sensing (corn yield goals, manure credits, and stage of crop development). However, N application rate based on corn yield goals has been found to be poorly correlated with optimum N rates (Doerge, 2002), which may limit the usefulness of this approach. In addition, proper crediting of N from animal wastes is difficult to estimate (Bausch and Diker, 2001). This approach also did not directly determine, from plant N stress sensing, how much N to apply. There still exists a need for an effective N rate determination method in rain-fed corn production where in-season N application would be limited to one application.

The objective of this study was to investigate the potential for developing a calibration between corn plant N deficiency stress monitored with the Minolta SPAD 502 CM and rate of fertilization required to provide economic optimal N.

Materials and Methods

This study utilized data from multiple N rate trials conducted across Iowa from 1999-2005, with a total of 74 site-years. Sites had either corn following soybean or continuous corn. There were three different sets of trials. The first set of trials were conducted from 2001-2003, with a total of 43 site-years located on producers fields. These sites were all corn following soybean. The second set of trials were conducted from 1999-2004, with 28 site-years located on research farms. These sites had both corn following soybean and continuous corn. The third set of trials were conducted from 2004-2005, with a total of 3 site-years located on producers fields. These sites were all corn following soybean.

The experimental design at all sites was a randomized complete block, with N rates replicated four times. The plot size was 6 or 8 rows wide by 15 m in length. The first set of trials had 6 N rates, ranging from 0-225 kg N ha^{-1} in 45 kg increments. The second set of trials had 7 N rates, ranging from 0-270 kg N ha^{-1} in 45 kg increments. One site in that set of trials had 5 N rates ranging from 0-270 kg N ha^{-1}, with 67.5 kg increments. The third set of trials had 6 N rates, ranging from 0-225 kg N ha^{-1} in 45 kg increments. The N fertilizer source varied across the trials; 46 sites with ammonium nitrate surface applied at crop emergence, 26 sites with urea applied spring preplant and incorporated, one site with urea-ammonium nitrate solution applied spring preplant and incorporated, and one site with ammonium nitrate applied sidedress.

Corn plant N stress detection was determined with the Minolta SPAD 502 CM following the procedure outlined in Peterson et al. (1993). Chlorophyll meter readings were taken from the ear leaf at the R1 corn growth stage (Ritchie, 1993). Each CM reading was taken midway between the stalk and tip of the leaf and midway between the midrib and margin of the leaf. The uppermost leaf with the collar fully visible was sensed on 20 to 30 different plants in the middle rows of the treatment plot, making an effort to avoid readings from non-representative corn plants. Relative chlorophyll meter values were calculated by dividing the site average CM readings for each N rate by the corresponding CM reading from the highest N rate.

At six of the second set of trial sites conducted in 2003, CM readings were collected at V8, VT, R1, and R3 corn growth stages. These sites were corn following soybean. All CM readings were collected according to the procedures outlined by Peterson et al. (1993). Readings were taken from the top most collared leaf until the VT growth stage, when readings were taken from the ear leaf. Relative chlorophyll meter values were calculated as described above.

The plots were harvested by hand (7.6 m length) from the center two rows of each plot or harvested with a plot combine from the center rows of the entire plot length. Grain yield was calculated on a 155 g kg^{-1} moisture basis.

Statistical analyses were run using SAS (version 9.1). Yield response to N rate at each site was analyzed by first using PROC GLM to determine whether N rate or mean N rate contrasted to zero N was significant ($p < 0.10$). The NLIN procedure was then used to fit regression models for those sites identified as N responsive. The model that was statistically significant and with the highest coefficient of determination (R^2) was selected. If the models had a similar R^2 values, the quadratic plateau or quadratic model was chosen. Each yield response fit was also visually inspected to confirm model choice. The economic optimum N rate (EONR) for each site was determined from the regression model at a 0.10 N fertilizer to corn price ratio. The N rate difference from the EONR (ND) was then calculated for each N rate at each site.

To determine the relationship between N rate, CM reading, and RCM values, all site CM and RCM values for each rotation were regressed against the corresponding ND. The PROC NLIN procedure was used to fit regression models, with the model that was statistically significant and with the highest coefficient of determination (R^2) being selected. The model fit was visually inspected to confirm model choice. When there were similar R^2 values, the quadratic plateau model was chosen.

Results and Discussion

The relationship between the direct CM readings and ND was not as good as the relationship between the calculated RCM values. This is visually and statistically evident in Figs. 1 and 2. From Fig. 1, it is evident that the relationship with CM readings is a poor fit ($R^2 = 0.53, p < 0.001$) for both deficit N (N rate less than zero differential from optimum N) and excess N (N rate greater than zero differential from optimum N). This was expected since previous research has shown that different field conditions, hybrids, and other various corn plant stresses influence CM readings (Schepers et al., 1992a; 1992b). Normalizing these readings to a well-fertilized reference area within the same field helps minimize these influences. Thus, there is a better relationship ($R^2 = 0.73, p < 0.001$) with the RCM values (Fig. 2) than the non-normalized CM readings ($R^2 = 0.53, p < 0.001$).

The shape of the relationship between RCM values and N differential is similar to that found by Piekielek et al. (1995) excess N and ear leaf CM readings at the early dent growth stage (Fig. 2). The RCM reaches a plateau at a 0.99 value, and when the ND is zero (at optimal N) the RCM value is 0.97. When RCM values fall below 0.97, there is an N stress deficiency. This 0.97 RCM value at optimal N is higher than the 0.95 value other researchers have found as a critical value indicating plant N stress (Peterson et al., 1993). For N rates greater than zero ND (excess N), the RCM values level off and do not increase with greater excess applied N. For RCM values less than zero ND (deficit N), the values decrease as N rates become more deficit. There are many RCM values at N rates slightly below the zero ND that are close to the same values as when N is adequate or excess, that is, close to 0.97 RCM. This is a portion of the regression model that does not appear to differentiate well between adequate, slightly deficit, and excess N. This could result in suggestions for low N rate application in-season when none is needed, or when there is only potential for a small yield increase to applied N.

The linear plateau and quadratic plateau models had similar regression fit ($R^2 = 0.72$ and $R^2 = 0.73$, respectively). We chose the quadratic plateau model to describe the relationship between RCM and N rate differential because the linear plateau model resulted in the segmented regression line join point being at a high deficit N rate, which would mean that the first increment of suggested N based on RCM N stress sensing would be at a high N rate. That rate would be 67 kg N ha^{-1}, which seems high to correct a slight plant N stress.

A quadratic-plateau regression model was determined for the RCM values at the 28 continuous corn sites (Fig. 3). The plateau is at a 1.01 RCM value, beginning at a ND of 84 kg N ha^{-1}. The RCM value at zero ND is 0.98. For corn following soybean, the plateau is at a 0.99 RCM value, beginning at a ND of 70 kg N ha^{-1} and the RCM value at zero ND is 0.97. The quadratic and linear plateau coefficients are similar, therefore the shape of the regressions are comparable. The coefficient of determination is similar ($R^2 = 0.76$ and $R^2 = 0.73$, respectively) for continuous corn and corn following soybean as well. Since the relationship between RCM and N rate are similar for both rotations, one calibration can be used for estimating in-season N rates in continuous corn as well as corn rotated with soybean.

At six of the second set of trial sites conducted in 2003 with corn following soybean, CM readings were collected at V8, V15, VT, R1 and R3 corn growth stages. The RCM values and fitted regression equations for each growth stage (RCM versus ND) are shown in Fig. 4 and Table 1. The RCM values with deficit N are largest at V8 and smallest at the R3 growth stage. The RCM values at V8 did not separate deficit and excess N as well as CM readings at the other growth stages. The RCM values change as corn N demand and uptake continues throughout the growing season, thus indicating increased N stress as deficiency persists or increases. Readings taken at R1 and R3 will provide a better estimate of season-long N deficiency or adequacy as the plant has integrated N uptake over a longer time period. These stages also give the smallest RCM values at deficit N rates, as indicated by the calculated RCM values and the regression equations (Table 1). The RCM values for the V15 and R1 growth stages are virtually the same (Fig. 4), suggesting there is a period of time during late corn vegetative growth, rather than one critical time, during which CM readings provide a similar indication of plant N stress and N application from the RCM based N rate calibration. This time period also is during significant corn N uptake, which is an important time for development and expression of N stress, and for making needed fertilizer N applications.

Conclusion

Regression analysis indicated a quadratic-plateau relationship between corn plant N status sensed with a Minolta SPAD CM and N rate differential from optimal N (ND). With increasing N stress, decreased CM readings and RCM values related to increased deficit N. With adequate to excess N (ND greater than optimal N), the relationship remained constant. That is, increasing excess N did not increase CM readings or RCM values. Variability in the relationship between ND and plant N stress was reduced significantly with use of normalized values (RCM values) compared to direct CM readings, demonstrating the importance of normalizing CM readings to minimize variability attributed to factors other than N stress. For corn following soybean, the R^2 associated with CM readings was 0.53 ($p < 0.001$), but 0.73 ($p < 0.001$) with RCM values. For corn following soybean, the RCM value at optimal N (zero ND) was 0.97, which is similar but slightly higher than the 0.95 value found in other studies.

For continuous corn, the relationship between RCM and ND was similar to that with corn following soybean indicating the same calibration for N application rate based on RCM values can be used for corn in both rotations. The similarity in RCM values found at V15 and R1 suggest that there is a period of time during late vegetative growth, rather than one critical time, to collect CM readings, obtain a similar indication of plant N stress and N rate to apply, and still provide time for in-season N application. The calibration between RCM values and differential from EONR found in this study could be used by producers to evaluate corn N stress in-season during mid-to late vegetative growth stages, determine if additional N is needed, and adjust N application rates on a field basis.

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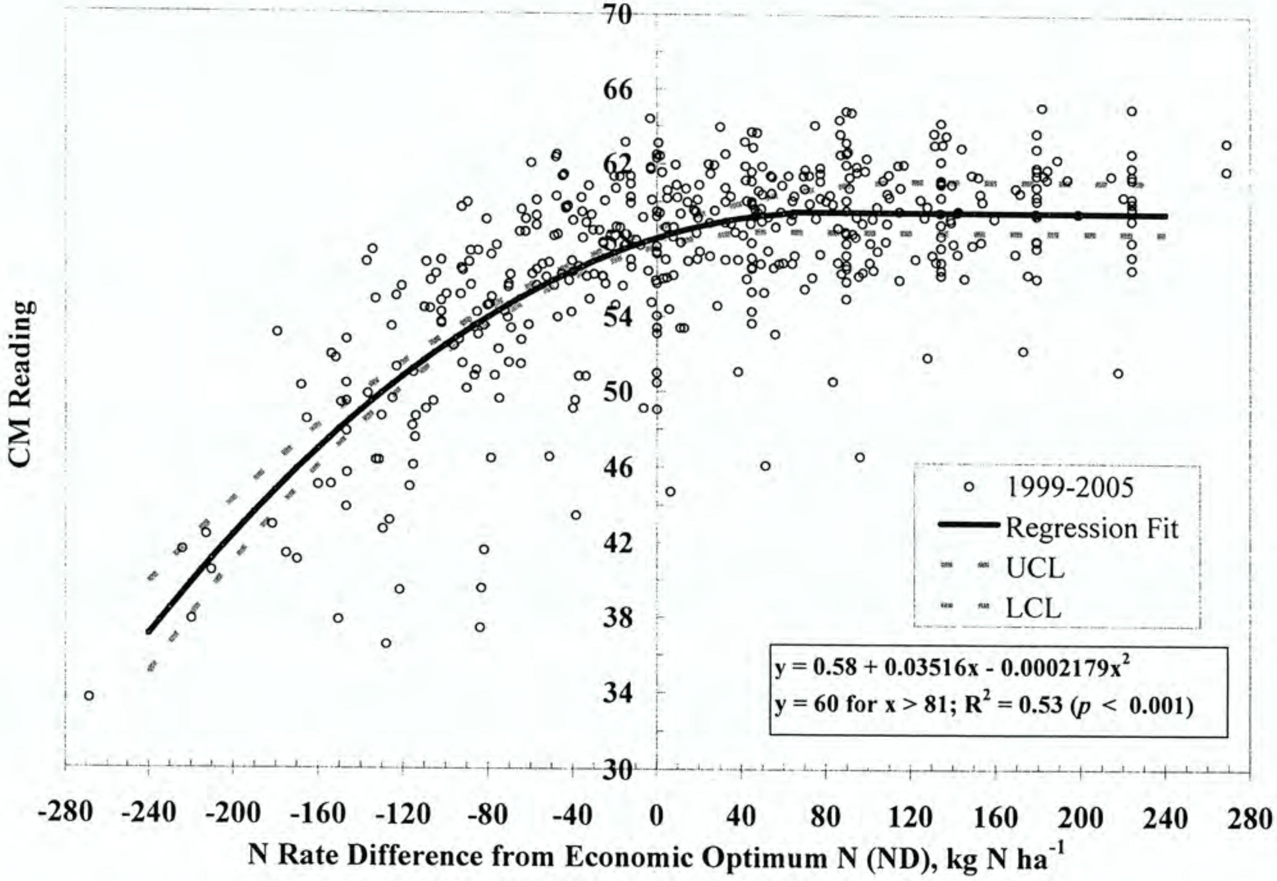

Figure 1. Chlorophyll meter (CM) readings at R1 corn growth stage as related to the N rate difference from the site optimum N rate (ND), corn following soybean at 74 site-years, 1999-2005. The UCL and LCL represent the upper and lower confidence limits ($p \leq 0.05$), respectively, of the fitted regression equation.

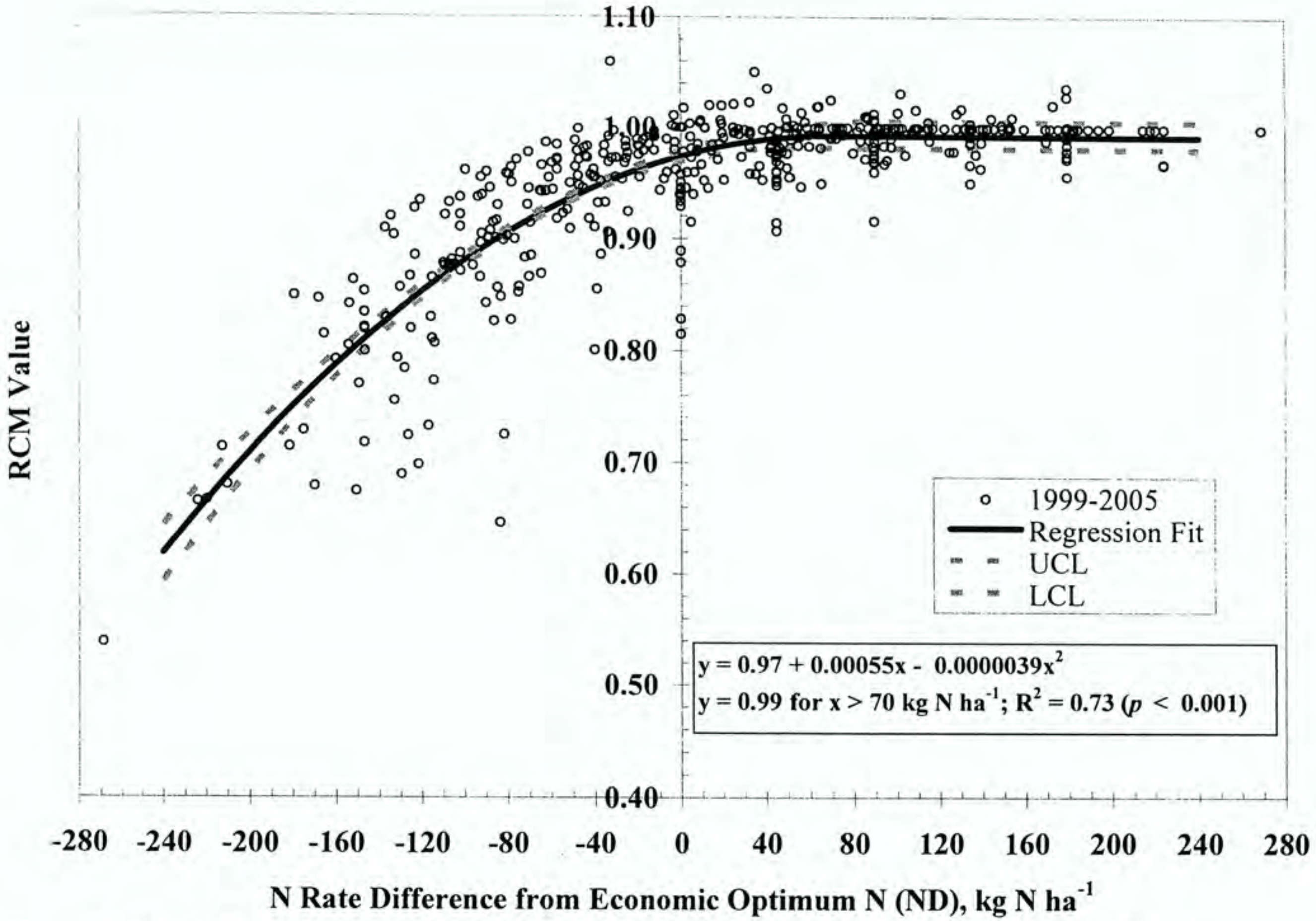

Figure 2. Relative chlorophyll meter values (RCM) at R1 growth stage as related to the N rate difference from the site optimum N rate (ND), corn following soybean at 74 site-years, 1999-2005. The UCL and LCL represent the upper and lower confidence limits ($p \leq 0.05$), respectively, of the fitted regression equation.

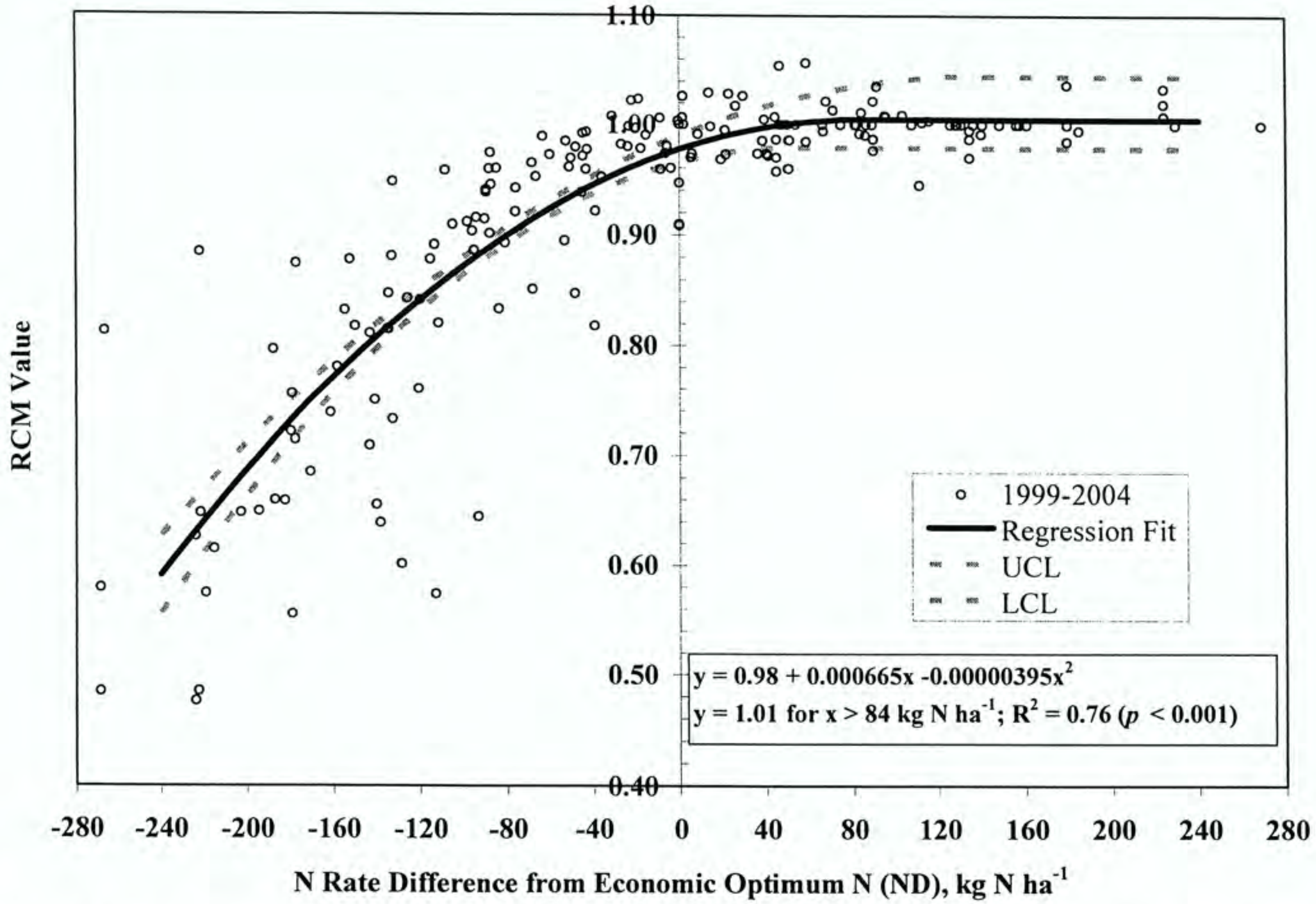

Figure 3. Relative chlorophyll meter (RCM) values at R1 growth stage as related to N the rate difference from the site optimum N rate (ND), continuous corn at 28 site-years 1999-2004. The UCL and LCL represent the upper and lower confidence limits ($p \leq 0.05$), respectively, of the fitted regression equation.

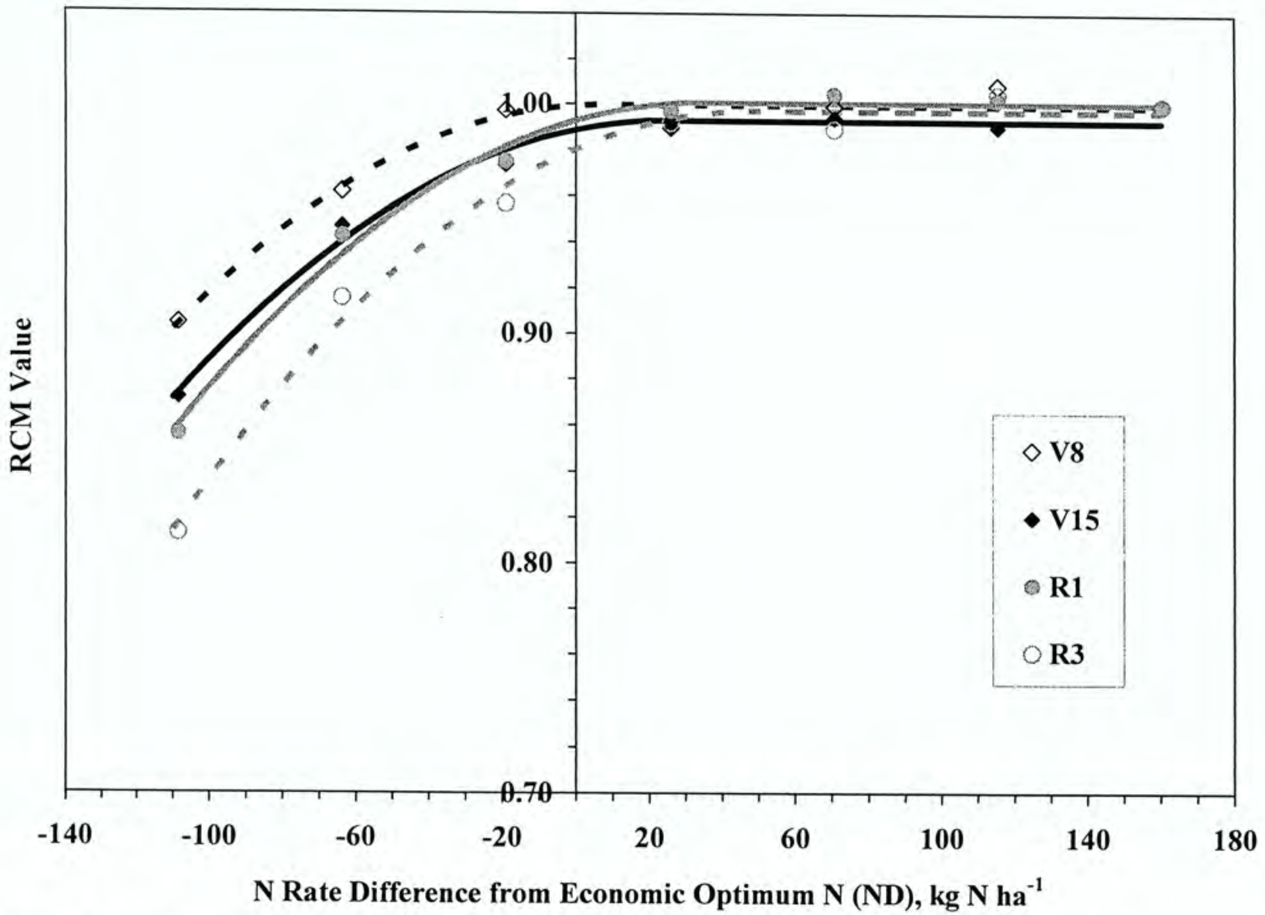

Figure 4. Average relative chlorophyll meter values at V8, V15, R1 and R3 corn growth stages as related to the N rate difference from the optimum N rate (ND), corn following soybean at 6 sites in 2003. Response curves were generated from regression models given in Table 1.

Table 1. Quadratic-plateau regression models for the relationship between relative chlorophyll meter (RCM) values and N rate differnece from economic optimum N at 6 corn following soybean sites in 2003.

Growth Stage[†]	Regression Model[‡]	Join Point	Plateau	R^2	*p*
		kg N ha^{-1}			
V8	$y = 1.00 + 0.00012x - 0.0000071x^2$	8	1.00	0.97	0.0007
V15	$y = 0.99 + 0.00034x - 0.0000066x^2$	26	0.99	0.99	0.0002
R1	$y = 0.99 + 0.00048x - 0.0000069x^2$	35	1.00	0.99	0.0001
R3	$y = 0.98 + 0.00071x - 0.0000073x^2$	49	1.00	0.99	0.0001

[†] Corn growth stages.

[‡] x, N rate difference from the EONR (ND), kg ha^{-1}; y, relative chlorophyll meter (RCM) value.

Demonstration of in-season nitrogen management strategies for corn production

A paper to be submitted to Agronomy Journal

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Abstract

Nitrogen is the largest fertilizer input for corn (*Zea mays* L.) production in Iowa. With rising N fertilizer prices, producers are looking to better manage their N inputs. A project designed to evaluate several potential N application timing strategies for improving application rate was conducted in cooperation with producers in Iowa cornfields. Our approach used low and agronomic N rates applied preplant or early sidedress (defined as PRE applications for this study), corn plant sensing with a Minolta SPAD 502 chlorophyll meter (CM) to detect N stress, and providing producers with an adjusted as-needed in-season N rate (in-season timing is application later than a traditional sidedress and after plant N stress sensing). The treatment structure consisted of field length strips, replicated three times with six different N rates; 0 (control), 67 (reduced rate), 67+ (plus in-season N), 134 (agronomic rate), 134+ (plus in-season N), and 268 kg N ha^{-1} (reference). There were 22 sites, all corn after soybean (*Glycine max* L. Merr.). Corn plants were sensed for N stress from V10 to VT growth stages. In order to determine in-season N application rate, a previously developed calibration was used that related relative (normalized) CM values (RCM) to economic optimum N rate (EONR). In-season N was applied with high clearance equipment before or at the R1 growth stage. Results demonstrated that N deficiency stress sensing was reasonably successfully with the 67+ and 134+ N rate strategies (68% and 82% correct N deficiency stress detection, respectively). These percentages were determined by evaluation of yield response to in-season applied N. The 67+ strategy had a total of 131 kg N ha^{-1} applied on average, but did not attain yields as high as the agronomic 134 PRE rate (mean yields were 11750 and 12340 kg ha^{-1}, respectively). When comparing the economic return of the various N application strategies, the 134 PRE and 134+ yielded the greatest with less cost (no or few in-season applications and no or little additional N) than the 67+ strategy. Economic return calculations indicate the PRE application rate of 134 kg N ha^{-1}, with affirmation of N stress and determination of additional N need through plant sensing, appears to be a more cost effective strategy than using a lower PRE N rate.

Abbreviations: EONR, economic optimum N rate; CM, chlorophyll meter; RCM, relative chlorophyll meter; PRE, N applied preplant or early sidedress.

Introduction

Nitrogen fertilization is a key component to corn production. Past N application practices and a desire for high yields, fueled by low fertilizer N costs, have led producers to over-apply N rather than falling short of crop N needs and risk costly yield losses. Due to increased environmental concerns, the susceptibility for nitrate leaching to ground water and loss in tile lines, and the rising costs of fertilizer N, producers are looking at management strategies that have the potential to improve N use efficiency and economic return to corn production.

Current N management practices based on yield goals have been found to be poorly correlated with optimum N rates (Vanotti and Bundy, 1994; Doerge, 2002; Nafziger and Sawyer, 2004). In addition, proper crediting of N from animal wastes and legume rotations, as well as estimating soil organic N mineralization, is difficult to estimate precisely (Bausch and Diker, 2001). Thus it is important to study emerging N management strategies so producers can benefit from and implement them if proven helpful and economical. Producers need N diagnostic tools that are capable of determining crop available N from the soil system so that applied N rates can better match crop fertilization needs. Economic optimum fertilization rates can vary widely by field and year (Nafziger and Sawyer, 2004), so N rate determination should be on a field specific basis.

One approach to better matching N application rate to crop N fertilization need is a split application, focusing the split component of the application at mid-to-late vegetative corn growth stages (in-season N). In-season refers to application of fertilizer later than the traditional early sidedress application timing. Applying N sidedress is a highly effective practice on coarse-textured soils, and is easily implemented when fertigation is practiced. On medium to fine textured soils in rain-fed corn production areas, research has indicated that split applications of fertilizer N are often equal to preplant N, but can sometimes be more effective than an all preplant application (Bundy, 1986; Randall and Schmitt, 1994; Killorn et al., 1995; White and Gress, 2002). The benefit of an in-season strategy includes not only applying N when the corn plant needs and utilizes N the most, but also providing an opportunity to better match N fertilization with crop requirements. Many methods have been investigated for assisting in determination of optimal N application rates, one being soil nitrate testing. A more recently investigated approach is corn plant N stress sensing.

Scharf (2001) evaluated soil and plant N analyses and plant N sensing to determine corn crop N status, finding that plant measures were more strongly related to optimum N rate. Blackmer and Schepers (1994) evaluated different techniques for monitoring N status in corn, including the stalk nitrate test and plant sensing. They identified the Minolta SPAD 502 CM as the best plant diagnostic tool, including the capability of detecting N deficiency stress. Utilization of this tool allows the corn crop to indicate differential N needs from year to year.

It has been well documented that CM readings are highly correlated with N concentration in corn leaf tissue (Piekielek and Fox, 1992; Wood et al., 1992; Schepers et al., 1992a; 1992b). The ability of the CM to accurately identify N deficiencies is improved when normalizing the CM reading to an adequately fertilized reference area within the same field (Schepers et al., 1992a; 1992b). This also allows interpretation across hybrids, fields, sampling dates, and other corn plant stresses. Subsequent research by Peterson et al. (1993) created the sufficiency index (SI), which indicates that when a corn crop has a RCM reading 95% as green as the reference area or less, additional fertilizer N is needed.

Nitrogen stress sensing is more accurate and successful later in the growing season. The important issue then is balancing what is needed for successful sensing of plant N deficiency stress with concerns associated with later determination of N need, such as wet fields, adequate plant N uptake and response to added N. It has been well established from studies of corn N uptake that important and large accumulation rates occur before/near silking (Ritchie et al., 1986). Research conducted by Russelle (1993) indicated that N recovery by corn may be greater when N application is delayed (split) than with a single blanket application at planting. He measured higher yields when N was applied at V8 or V16 growth stages than when it was applied at V4. A study by Scharf et al. (2002) comparing in-season N application timing and yield recovery found little or no yield loss when in-season N application was delayed to the V11 growth stage (even under high stress) and only a 3% yield loss when delayed until V12 to V16. Application at R1 in that study did not result in full yield potential, but the corn crop was still highly responsive to the late applied N. Contrary to these findings, Binder et al. (2000) reported that corn yields declined when N applications were delayed, even with just moderate plant N stress, and that yield recovery was limited if stress was more severe or in-season N application was delayed. In the first year of the Binder et al. (2000) study, significant yield reduction was seen as early as V6, and at VT in the second year. According to Russelle et al. (1983), in most instances in-season N should be applied by the VT to R1 corn growth stages.

Once N deficiency stress is identified, it becomes important to determine N application rates to correct the identified deficiencies. Some researchers have concluded that the CM is not capable of providing information for making such recommendations (Piekielek and Fox, 1992; Bullock and Anderson, 1998). Contradicting this, Vetsch and Randall (2004) found that RCM values at late vegetative growth and early reproductive stages were highly correlated to relative corn grain yield and could be used to determine sidedress N needs under non-irrigated conditions. Several researchers have substantiated this by using the CM to predict in-season N rates for irrigated corn (Blackmer and Schepers, 1995; Francis and Piekielek, 1999). These studies show that CM readings have a good relationship with yield; however, that research did not include development of a relationship that would estimate what N rate to apply, especially when only one in-season application is to be made. In irrigated conditions, Peterson et al. (1993) suggested that a small (about 50 kg N ha^{-1}) rate be applied in-season if RCM values were less than 0.95, sense the crop again, and apply another small rate of N if deficiency persisted or recurred. Fertigation makes this approach manageable; however, multiple in-season N applications are likely not feasible for rain-fed corn production due to cost and time constraints.

A calibration relating RCM value to N rate differential from economic optimum, that is, an estimate of needed N application rate, was presented in Chapter 1 for corn following soybean and corn after corn. With this N rate estimation, it is possible through corn plant N deficiency/sufficiency sensing to determine if adequate N is available to the plant, and to arrive at an application rate to offset N stress.

We had three main objectives for this study. First, demonstrate the use of corn plant N deficiency stress monitoring to determine need and rate of in-season N application. Second, demonstrate the effect of two PRE applied N rates on corn N sufficiency/deficiency, plant N stress development, need for additional N applied in-season, and corn response to N applications. Third, compare corn yield response and economic return with use of PRE applied N rates versus PRE applied rates plus in-season N application.

Materials and Methods

This study was conducted in cooperation with producers at 22 field sites located throughout Iowa (Table 1). All locations were corn following soybean and varied in soil, tillage system, yield history, manure application history, and source-timing of PRE fertilizer N application. Site characteristics are given in Table 2.

There were six initial PRE rates applied either preplant or early sidedress as field length strips. These are identified as PRE N and consist of: a zero N, a non-limiting N reference rate of 268 kg N ha^{-1}, an agronomic N rate of 134 kg N ha^{-1} based on the midpoint of Iowa State's current N recommendations for corn following soybean, Blackmer et al., (1997), a reduced N rate of 67 kg N ha^{-1} (half of the agronomic rate), and two in-season applications based on corn N stress sensing. One in-season application would be in addition to the reduced PRE N rate of 67 kg N ha^{-1} (referred to as 67+), and the second in-season application would be in addition to the agronomic PRE N rate of 134 kg N ha^{-1} (referred to as 134+). In this study, in-season refers to N applications made later than traditional sidedress timing, which would also be after any early sidedress PRE N application. The timing and source of PRE N applications are given in Table 3, while the treatment structure is outlined in Table 4. The experimental design was a randomized complete block, replicated three times. All strip treatments were at least 12 rows wide and ranged in length from 250 to 800 m.

This treatment structure allows evaluation of two potential N management strategies for improving N application rates. The first strategy involves applying a reduced PRE N rate, with the expectation that in-season N will be applied most years, but might provide producers with a more accurate determination of total crop N need from year to year. This should also identify fields where considerably less N is needed than the agronomic N rate. The second strategy involves applying an agronomic PRE N rate, then using the CM to detect N stress deficiencies in-season as a rescue measure for those years when the agronomic N rate is not adequate.

Nitrogen stress detection was determined with the Minolta SPAD 502 CM following the procedure outlined in Peterson et al. (1993). Chlorophyll meter readings were collected from the top most collared leaf from V10 until VT corn growth stage (Ritchie et al., 1993), when readings were taken from the ear leaf. Care was taken to sample midway between the stalk and tip of the leaf and midway between the midrib and margin of the leaf. Readings were collected from the uppermost leaf with the collar fully visible leaf on 20 different plants within 10 m of flagged points in the middle of the treatment strips, making an effort to avoid readings from non-representative corn plants. Flagged points were spaced approximately 45 m apart along the treatment strips. Chlorophyll meter readings were collected in each strip at 5 to 10 locations (flagged points), depending on the strip length. Relative chlorophyll meter values were calculated by dividing the mean readings at each strip location by the corresponding reading from the N reference strip within that replicate. Once RCM values were calculated for each location within a treatment strip, the mean of those values was used as the N sufficiency/deficiency indicator for each treatment and to determine in-season N rate need for the 67+ and 134+ treatments.

The in-season N application rate was calculated using the RCM value calibration from Chapter 1. Additional N was applied to the 67+ and 134+ treatments when identified as deficient by RCM values. The RCM value at zero deviation from the EONR is 0.97. A RCM above this value indicates corn has adequate N and no additional N is needed. A value less than 0.97 indicates plant N stress at a level where additional N is required. This value is slightly more conservative than the 0.95 value found in other research (Peterson et al., 1993; Blackmer and Schepers, 1995). We set a 34 kg N ha^{-1} minimum and a 112 kg N ha^{-1} maximum in-season application rate. The maximum was set because of the expectation that it would be cost prohibitive to apply more than 167 kg total N ha^{-1} as a total N application for corn following soybean and to optimize N use, also given the timing of in-season application. We decided application costs would not justify making an application of less than 34 kg N ha^{-1}. Also, based on site variation in determining the calibration equation, at or slightly below a RCM value of 0.97 it would be difficult to differentiate sufficiency or deficiency. Using the 34 kg N ha^{-1} minimum in-season N rate makes the 0.97 RCM N cutoff value equivalent to the

RCM value of 0.95 other researchers have established. Table 5 shows the minimum RCM value and rate, and the in-season N rates indicated at other RCM values.

All field activities, except for N stress sensing, were completed by the producer, including PRE N applications and grain harvest of the treatment strips. All in-season fertilizer N was applied as urea-ammonium nitrate (UAN) solution with high clearance equipment using either drop nozzles (surface dribbled) or coulter-injected into the soil. Producers harvested either the middle 6-8 rows or the full width of each strip. Harvest was completed with combines equipped with yield monitors, most with Global Positioning Systems (GPS) technology, or with weigh wagons. Corn grain yields were adjusted to 155 g kg^{-1} moisture.

For yield monitor determined yields, data was cleaned by eliminating individual yield monitor data points that fell outside of 3 standard deviations from the mean of each treatment strip. Treatment strips were saved as separate loads and referenced with previously established GPS coordinates within each field. Data was analyzed using PROC GLM in SAS (version 9.1) for mean separation to determine significant differences between treatment yields. A significance level of 0.10 was used to determine significant differences.

Economic net return was calculated by subtracting the mean fertilizer cost plus an in-season N application cost from the mean yield gain for each treatment. There were four assumptions made in calculating net return. First was a corn price of \$0.09 kg^{-1}. We chose this price because it is the approximate price for corn in Iowa when all current government program payments are included. The second assumption was \$0.66 kg^{-1} N. This is approximately the price for fertilizer N in Iowa during the study period. Third was a \$3.24 ha^{-1} charge associated with in-season N application. We arrived at this amount as a direct quote from industry. No charge was included for the PRE N application as this would not vary by rate at each site. Finally, there was no fee included for corn N stress sensing. Obviously there would be an additional cost for this; we chose not to include it in our calculations because that cost was not established at the time of the study. Calculations are as follows: the N cost increase was calculated by taking the N application increase times \$0.66 kg^{-1} N cost plus a fraction of the \$3.24 application charge (the number of sites receiving in-season N out of the total number of sites for each in-season treatment). The income gain/loss was calculated taking the yield gain/loss times the \$0.09 kg^{-1} price for corn. Net return is the difference of these two values. For this economic analysis, the N application and yields were averaged across all sites, not just those sites where additional N was applied.

Results and Discussion

Nitrogen Application

All 22 sites were responsive to applied N (Tables 6 and 7). With the 67 PRE N rate, all but one site had RCM values that indicated a need for additional in-season N. Where in-season N was applied, the mean rates were 61 kg N ha^{-1} and ranged from 34 to 129 kg N ha^{-1} (Table 6). This mean and range does not include Site 9 which had an in-season application rate of 180 kg N ha^{-1}. That rate was double the suggested rate due to improper boom width calibration, and exceeded the maximum rate set by our protocol by 67 kg N ha^{-1}. The second highest rate applied in-season (129 kg N ha^{-1}) also exceeded our maximum set by protocol. This recommendation was given to the producer by mistake instead of the maximum of 112 kg N ha^{-1}. Relative chlorophyll meter values for the 134 PRE N treatment indicated N deficiency stress at 4 sites and need for an in-season N application. However, 6 sites had additional N applied. Two of the cooperating producers (at sites 17 and 18) wanted to apply less than 34 kg N ha^{-1} in-season N to the 134+ treatment, despite our protocol of not applying additional N if the RCM values indicated less than 34 kg N ha^{-1}. Thus, where in-season N was applied, the mean rates were 40 kg N ha^{-1} and ranged from 17 to 67 kg N ha^{-1}.

Site 14 did not have any in-season N applied with both PRE N rates since the RCM values indicated none was needed. This was the correct decision since yield was not statistically different than the 268 reference for both the 67 and 134 PRE N treatments at this site. If in-season N had been applied according to our N rate determinations at each site (without the double application or application of less than 34 kg N ha^{-1}), the mean N rate applied (PRE plus in-season) at only those sites that called for additional N would have been 129 and 169 kg N ha^{-1} for the 67+ and 134+ treatments, respectively.

Chlorophyll Meter Sensing

Success in sensing N sufficiency or N stress deficiency was determined from yield results that are given in Table 7. Plant N stress sensing indicated that 21 of the 22 sites needed additional N with the 67 PRE N rate. Of these 21 sites, 14 had higher yields with this in-season N application. The 67 PRE N rate did not have a significant yield difference from the 268 reference at 8 sites. Nitrogen stress sensing only correctly identified one of these 8 sites as being N sufficient (site 14). Five of 7 sites had N stress sensing that indicated a small additional N need (34 to 39 kg N ha^{-1}), but had no yield response to the in-season N application. This region of the application rate calibration, slight N stress and low N application, might not be sensitive enough to adequately differentiate between N sufficiency and N deficiency. Overall, N stress sensing with the 67 PRE rate was 68% successful at detecting N stress sufficiency/deficiency. This was determined by taking the number of sites correctly identified as being N sufficient or having N deficiency stress, divided by the total number of sites.

Sensing in the 134 PRE N treatment indicated that 4 of the 22 sites needed additional N. Six sites received in-season N because two producers applied less than 34 kg N ha^{-1} despite our protocol. Two of the 6 sites that had in-season N applied were correctly identified as being N deficient. Three of those sites were N sufficient when sensing indicated an N deficiency. Sensing missed one site that needed additional N, however, it did in fact receive N since it was one of the two sites that had less than 34 kg N ha^{-1} applied (site 17). Sensing with the 134 PRE N rate was 82% successful at correctly identifying which sites were N sufficient/deficient.

Site 21 had decreased yield with in-season N application to both the 67+ and 134+ treatments. There was no visible burning of the leaves from UAN or physical plant damage from application of in-season N, so we attribute this to experimental error.

Corn Yield

Grain yield was significantly increased (above the control) with the PRE 67 and 134 kg N ha^{-1} rates at all 22 sites (Table 7). Yield was significantly higher with the 134 PRE compared to the 67 PRE N rate at 15 of the 22 sites. Of the 14 sites where sensing correctly identified N deficiency with the 67 PRE N treatment, 8 had a significant yield increase to additional N. With 134 PRE N, only 2 of the 6 sites with in-season applied N had a significant yield increase to the additional N. Nineteen of the 22 sites yielded statistically similar to the 268 reference N rate when the agronomic 134 PRE N rate was applied. Site 21 had a significant yield decrease following in-season N application to both the 67+ and 134+ N rate treatments.

The sites with the greatest response to in-season N application had a 2380 and 2000 kg ha^{-1} increase (sites 9 and 17, respectively). Site 9 had double the suggested N rate applied in-season, which brought total N application to 246 kg N ha^{-1} in the 67+ treatment instead of the prescribed total of 123 kg N ha^{-1}. Site 17 had in-season N applied at V13 and received 7.29 cm of rainfall after application. Two other sites with large yield response to in-season N (sites 12 and 15) also received considerable amounts of rainfall (after N application at R1). The mean yield increase of the 8 sites that had a significant response to in-season N with the 67+ treatment was 1250 kg ha^{-1}.

When comparing method of in-season N application to the 67+ treatment, 2 of the 8 sites that were coulter injected had a significant yield increase to additional N, however, the increase was not enough for yield to be statistically similar to the 268 reference N rate. Of the 13 sites that used drop nozzles for in-season N application on the 67+ treatment, 6 sites had a significant yield increase and one site had a significant yield decrease. Only one site had a yield response that was statistically similar to the 268 reference N rate. These results indicate that method of in-season N application did not enhance or detract from potential response to in-season N.

Total N application and yield summary across the 22 sites is given in Table 8. There was a mean yield increase across all sites of 500 kg ha^{-1} from the in-season N applied to the 67 PRE rate (when comparing the 67 PRE to the 67+ N rate treatments). There wasn't any mean yield difference between the 134 PRE and 134+ N rate treatments. This is due to the fact that sensing found very few sites to be deficient over the two years with this PRE N rate.

On average, the 134 PRE N rate had a 590 kg ha^{-1} and 1090 kg ha^{-1} higher yield than the 67+ and 67 PRE N rate treatments, respectively. The 67+ N rate had a mean total of 131 kg N ha^{-1} applied (basically the same total N as with the 134 PRE rate), but did not attain yields as high as the agronomic PRE N rate of 134 kg N ha^{-1}.

Economic Analysis

Table 9 demonstrates four different N application strategy and rate comparisons and the economic return associated with those comparisons. The table includes differences in mean total N applied and mean yield between treatments (calculated from Table 8), while taking into consideration the four assumptions outlined in the materials and methods. The treatment comparisons in the first column represent four different scenarios. The subsequent columns reflect what would happen if the producer switched from the first treatment listed to the second treatment.

For example, changing from a single 67 PRE N rate to a 67 + in-season N treatment increased yield by 500 kg ha^{-1}, however, there is the added fertilizer cost of 64 kg N ha^{-1} and the in-season application charge. The yield gain did not surpass the added costs; therefore, using the 67+ in-season management strategy would result in lower economic return. When comparing the 67 PRE with the 67+ in-season N, the additional N and application costs clearly results in this in-season N application strategy having a lower net return to the producer. The results are similar when comparing the 134 PRE N with the 134+ in season application strategy.

Since there was no mean yield difference between the 134 PRE and 134+ treatments, we chose to use the 134 PRE N application for comparison with the 67 PRE and 67+ in-season strategy (Table 9). The 134 PRE N had a 1090 kg ha^{-1} yield advantage over the 67 PRE. Since there is no in-season N application or other associated costs with either of these treatments, the 134 PRE gave a much better return to the producer. There was not as great of a yield advantage between the 134 PRE and the 67+ treatment comparisons (590 kg ha-1). However, the costs associated with additional N and in-season application with the 67+ strategy result in the 134 PRE having a greater return to the producer financially. Comparing the 67 PRE and 67+ with the 134+ would still give a larger net return for the 134+, however, the cost for any in-season application charge and additional N would decrease the return and economic advantage. The 134 rate gives a higher yield and greater economic return than either the 67 PRE or the 67+ in-season strategy, thus the 134 PRE N application is clearly the best choice economically when weighing the costs related to in-season N application and mean yield return associated with each strategy. These results occur despite the fact that some sites did not require the full 134 kg N ha^{-1} PRE N rate and less N could have been applied to those sites.

Other Considerations

One drawback of the 134 PRE strategy is that fields where 67 kg ha^{-1} is adequate, and attain full yield at that rate or lower, are overlooked. There is no way to identify the sites that would benefit from a lower N rate if the 134 PRE rate strategy is adopted.

Regression analysis could be used to determine corn response to N rate at each site. This requires curve fitting to the PRE N rates, which is problematic for model choice and confidence in the estimate of needed N since there are only four available N rates. A general examination of N response for the 22 sites, using both linear-plateau and quadratic-plateau models, indicated that all sites were responsive to N and the minimum N rate needed was at or above the lowest PRE rate of 67 kg N ha^{-1} (data not shown). This indicates the 67 PRE N rate was a reasonable minimum rate and should not often result in more N being applied than needed. Thus, the low PRE N strategy, for corn following soybean, should minimize potential for missing fields where very little N is required. That is, minimize potential for over-application to occur before in-season N stress sensing is used to determine if additional N is needed. Corn in some fields could be non-responsive to N application, but none had that response in this study.

There also is room for improvement in regard to the success of the plant N sufficiency/deficiency sensing. With both the 67+ and 134+ N strategies, the majority of sites that were incorrectly identified as being deficient only called for an additional 34 or 39 kg N ha^{-1}. Perhaps the minimum of 34 kg ha^{-1} we set to warrant in-season N application was not high enough to provide adequate crop recovery from the N stress. Or, perhaps the application rate calibration of the instrument (CM) may not be sensitive enough to correctly differentiate sufficiency/deficiency at low N stress levels and low indicated in-season N rates.

A final issue is that perhaps the timing of in-season sensing and N application was too late for growing conditions in Iowa. Our protocol was designed to take advantage of later season sensing for a more accurate indication of total corn N need. This delayed application to R1 at many sites, which other researchers have suggested is approximately the latest possible timing for in-season N application. Studies have shown that full yields can still be attained with in-season application at this stage; however, other researchers suggest applying N earlier. Targeting N stress sensing closer to V10-V15, with quick N application turnaround at or near V15 might be a better choice for Iowa's growing conditions. At the site with large yield increase to in-season N application (2000 kg ha^{-1}) and largest RCM increase (data not shown), the N stress sensing and application were completed by the V13 growth stage, and a significant rainfall occurred soon after N was applied. This is an area for further research. There didn't appear to be any definitive advantage from using drop nozzles or coulter injection of in-season N. Drop nozzles would be cheaper for producers since coulter bars are quite costly.

Conclusion

Results demonstrated that in-season plant N sufficiency/deficiency sensing was partially successful with both the 67+ and 134+ strategies. There was better success (based on comparison of yields) with the 134+ strategy (68% compared to 82%). Corn N stress development was found more frequently with the reduced PRE 67 kg N ha^{-1} rate than with the agronomic PRE 134 kg N ha^{-1} rate. Use of N stress sensing and applying additional N (the 67+ strategy) did not attain mean yields as high as the 134 PRE N or 134+ strategies. When comparing the 67+ and 134+ N management approaches, there are risks involved with the 67+ strategy influencing potential yield losses, especially when considering the total N applied was almost the same as the 134 PRE N rate. These risks include: a need for precipitation after in-season N application for plant N uptake, wet soil conditions that may prevent or delay in-season application, and the availability and cost of high-clearance application equipment. Economic return indicated that the PRE application rate of 134 kg N ha^{-1}, with affirmation of additional N need through plant N stress sensing, appears to be a more desirable strategy than using a reduced PRE N rate.

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Table 1. Site location, dominant soil, and tillage system for the 22 sites.

Site	Year	County	Dominant Soil Series	Classification	Tillage System
1	2004	Cerro Gordo	Floyd l	Fine-loamy, mixed, superactive, mesic Aquic Hapludolls	Minimum
2	2004	Dallas	Coland sicl	Fine-loamy, mixed, superactive, mesic Cumulic Endoaquolls	Minimum
3	2004	Kossuth	Canisteo cl	Fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls	Minimum
4	2004	Marshall	Tama sicl	Fine-silty, mixed, superactive, mesic Typic Argiudolls	None
5	2004	O'Brien	Sac sicl	Fine-silty, mixed, superactive, mesic Oxyaquic Hapludolls	Strip
6	2004	Palo Alto	Clarion l	Fine-loamy, mixed, superactive, mesic Typic Hapludoll	Minimum
7	2004	Shelby	Monona sil	Fine-silty, mixed, superactive, mesic Typic Hapludolls	None
8	2004	Shelby	Zook sicl	Fine, smectitic, mesic Cumulic Vertic Endoaquolls	Minimum
9	2004	Wapello	Richwood sil	Fine-silty, mixed, superactive, mesic Typic Argiudolls	Minimum
10	2005	Boone	Clarion l	Fine-loamy, mixed, superactive, mesic Typic Hapludoll	Minimum
11	2005	Dallas	Nicollet cl	Fine-loamy, mixed, superactive, mesic Aquic Hapludolls	Strip
12	2005	Dallas	Nicollet cl	Fine-loamy, mixed, superactive, mesic Aquic Hapludolls	Minimum
13	2005	Franklin	Clarion l	Fine-loamy, mixed, superactive, mesic Typic Hapludoll	Minimum
14	2005	Greene	Marna sicl	Fine, montmorillonitic, mesic Typic Haplaqualls	Minimum
15	2005	Grundy	Clyde sicl	Fine-loamy, mixed, superactive, mesic Typic Endoaquolls	Minimum
16	2005	Guthrie	Clarion l	Fine-loamy, mixed, superactive, mesic Typic Hapludoll	Minimum
17	2005	Marshall	Tama sicl	Fine-silty, mixed, superactive, mesic Typic Argiudolls	None
18	2005	Monona	Luton sic	Fine, smectitic, mesic Typic Endoaquerts	Strip
19	2005	Page	Colo-Judson sicl	Fine-silty, mixed, superactive, mesic Cumulic Endoaquolls Fine-silty, mixed, superactive, mesic Cumulic Hapludolls	None
20	2005	Shelby	Monona sil	Fine-silty, mixed, superactive, mesic Typic Hapludolls	Minimum
21	2005	Shelby	Zook sicl	Fine, smectitic, mesic Cumulic Vertic Endoaquolls	Minimum
22	2005	Webster	Nicollet cl	Fine-loamy, mixed, superactive, mesic Aquic Hapludolls	None

Table 2. Routine soil tests and site yield history obtained from cooperating producers.

					Yield History[†]	
Site	pH	STP[‡]	STK[‡]	OM[‡]	Corn	Soybean
		--- $mg\ kg^{-1}$ ---		$g\ kg^{-1}$	----- $kg\ ha^{-1}$ -----	
1	6.8	84	192	60	5330[§]	3090
2	6.3	85	258	- -[¶]	9160	2820
3	7.3	24	228	43	11920	3230
4	6.9	57	190	47	11100	3700
5	6.4	29	199	46	10660	3430
6	7.7	6	195	- -	8780	2760
7[#]	6.6	27	230	25	11600	3360
8[#]	7.1	119	406	43	9160	2760
9[#]	6.1	78	216	34	10220	2820
10	5.7	21	138	39	10910	3430
11	6.2	31	158	33	9340	3160
12	6.4	23	131	- -	9090	3830
13[#]	7.0	110	287	46	10350	3430
14[#]	6.2	13	252	50	11290	3090
15	6.9	34	159	43	11100	3560
16	- -	46	203	- -	10660	3430
17	7.0	48	167	48	11100	3290
18	6.4	15	330	35	7340	2820
19	- -	- -	- -	- -	6400	2690
20	7.0	144	437	37	10220	3360
21	7.0	184	380	40	9340	3360
22	- -	- -	- -	- -	10970	3290

[†] Yield history is an average of the last five to six crop years.

[‡] Soil test P (STP) is Bray P-1 or Mehlich-3 P, soil test K (STK) is ammonium acetate extractable K, and OM is organic matter.

[§] Seed corn yield history.

[¶] Not available.

[#] Manure application history in last 5 years.

Table 3. Corn planting data and PRE N application timing, method and N fertilizer source.

Site	Planting Date	Application Timing and Method	N Source
1	April 28	Early sidedress (V3)[†] -- Injected	UAN[‡] solution
2	April 17	Spring preplant -- Injected	Anhydrous ammonia
3	April 28	Early sidedress (V7) -- Injected	UAN solution
4	May 3	Early sidedress (V5) -- Surface applied	UAN solution
5	April 27	Pre-emergence -- Surface applied	UAN solution
6	May 5	Pre-emergence -- Injected	UAN solution
7	April 22	Pre-emergence -- Surface applied	UAN solution
8	April 27	Pre-emergence -- Surface applied	UAN solution
9	April 28	Early sidedress (V4) -- Surface applied	UAN solution
10	April 18	Fall preplant -- Injected	Anhydrous ammonia
11	April 15	Spring preplant -- Injected	Anhydrous ammonia
12	April 15	Spring preplant -- Injected	Anhydrous ammonia
13	April 28	Early sidedress (V4) -- Injected	Anhydrous ammonia
14	April 18	Fall preplant -- Injected	Anhydrous ammonia
15	April 18	Spring preplant -- Injected	Anhydrous ammonia
16	April 15	Pre-emergence -- Injected	UAN solution
17	May 2	Early sidedress (V6) -- Injected	UAN solution
18	April 30	Post-emergence (V2) -- Broadcast Surface applied	UAN solution
19	May 3	Early sidedress (V3) -- Injected	UAN solution
20	April 28	Pre-emergence -- Broadcast Surface applied	UAN solution
21	April 27	Pre-emergence -- Broadcast Surface applied	UAN solution
22	April 18	Fall preplant -- Injected	Anhydrous ammonia

[†] Vegetative corn growth stages, Ritchie et al. (1993).

[‡] Urea-ammonium nitrate (UAN) solution.

Table 4. Nitrogen application treatments.

PRE N Rate[†]	In-season N Application	N Application Treatment	Treatment Identifier
kg N ha^{-1}			
0	- - - - -	Control	0
67	- - - - -	PRE reduced[‡] N rate	67
67	At rate determined in-season	PRE reduced N rate + inseason	67+
134	- - - - -	PRE agronomic[§] N rate	134
134	At rate determined in-season	PRE agronomic N rate + in-season	134+
268	- - - - -	PRE reference[¶] N rate	268

[†] N rate for corn following soybean. PRE N refers to N applied from preplant to early sidedress.

[‡] Reduced is one-half of the agronomic N rate.

[§] Agronomic rate determined as approximate midpoint of current 112 to 168 kg N ha^{-1} range for corn following soybean suggested in Iowa State University publication pm-1714 (Blackmer et al., 1997).

[¶] Reference N is a rate to ensure adequate N and no corn N deficiency stress.

Table 5. Determination of in-season N rate based on relative chlorophyll meter (RCM) values.

RCM Value	N Rate To Apply
	kg N ha^{-1}
<0.864	112
0.880	101
0.894	90
0.907	78
0.920	67
0.931	56
0.941	45
0.951	34
0.959	22
0.967	11
0.973	0

Table 6. In-season N applications, relative chlorophyll meter (RCM) N stress values and post in-season N application precipitation.

	N Application		Sensing	None	67+			134+			
Site	Method	Timing	Timing	RCM Value	RCM Value	In-Season N[†]	Total N Applied	RCM Value	In-Season N[†]	Total N Applied	Precip.[‡]
						- - kg N ha^{-1} - -			- - kg N ha^{-1} - -		cm
1	Coulter Injected	R2	V15	0.90	0.96	34	101	0.98	- -	134	8.84
2	Coulter Injected	R2	V15	0.57	0.85	129	196	0.95	50	185	3.53
3	Coulter Injected	R1	VT	0.88	0.94	39	106	0.98	- -	134	3.89
4	Drop Nozzle	R1	VT	0.66	0.93	62	129	0.99	- -	134	6.02
5	Drop Nozzle	R1	VT	0.83	0.96	34	101	1.01	- -	134	6.60
6	Coulter Injected	R1	V13	0.84	0.93	90	157	1.01	- -	134	1.80
7	Coulter Injected	R1	V15	0.89	0.97	34	101	0.98	- -	134	7.57
8	Coulter Injected	R1	V15	0.91	0.96	34	101	0.98	- -	134	7.57
9	Drop Nozzle	R2	VT	0.76	0.91	179[§]	246	0.94	67[§]	201	2.59
10	Drop Nozzle	R1	V14	0.85	0.93	67	134	0.97	- -	134	3.10
11	Drop Nozzle	R1	V13	0.77	0.95	39	106	0.97	- -	134	6.53
12	Drop Nozzle	R1	V13	0.77	0.93	62	129	1.00	- -	134	6.58
13	Coulter Injected	R1	VT	0.88	0.96	34	101	0.99	- -	134	10.34
14	- - -	- -	VT	0.90	0.97	- -[¶]	67	0.98	- -	134	- -
15	Drop Nozzle	R1	V15	0.77	0.91	78	145	0.98	- -	134	11.86
16	Coulter Injected	R1	V14	0.83	0.95	45	112	0.99	- -	134	6.32
17	Drop Nozzle	V13	V13	0.81	0.89	95	162	0.97	22[#]	156	7.29
18	Drop Nozzle	V15	V15	0.83	0.90	90	157	0.97	17[#]	151	1.91
19	Drop Nozzle	VT	VT	0.75	0.90	67	134	1.03	- -	134	13.06
20	Drop Nozzle	R1	V14	0.86	0.90	90	157	0.96	34	168	4.90
21	Drop Nozzle	R1	V15	0.82	0.94	62	129	0.94	50	184	4.90
22	Drop Nozzle	R2	VT	0.87	0.96	34	101	0.98	- -	134	1.14

[†] In-season N application was urea-ammonium nitrate solution (UAN).

[‡] Precipitation (Precip.) totals recorded at nearby weather stations during the 2-week interval after in-season N application.

[§] Double suggested N rate applied due to improper boom width calibration.

[¶] Relative chlorophyll meter values indicated no in-season N needed, thus none was applied.

[#] Cooperating producers decided to apply N at rates less than 34 kg N ha^{-1}.

Table 7. Effect of PRE N rate and in-season N application on field-length treatment strip corn grain yield.

Site	N Application Treatment					
	None	67	67+	134	134+	268
	---------- kg ha^{-1} ----------					
1	9600a[†]	11980b	12480b	11980b	12540b	13230b
2	7590a	11160b	12230c	12980d	13420e	13670e
3	11920a	14610b	14110b	16050c	15800c	16430c
4	5710a	9910b	10720c	11920d	11920d	12230d
5	7590a	10220b	10910b	11980c	11980c	12540c
6	8910a	10030b	10850c	11730d	11230d	11920d
7	12920a	14170b	14550b	14360b	14550b	14550b
8	11730a	13110b	13110b	14170c	14240c	14610c
9	7590a	11920b	14300cd	13800c	14740d	13670c
10	8840a	10790b	11230c	11410cd	11290c	11730d
11	6650a	9280b	9530bc	10220cd	10470d	10030bcd
12	7020a	10600b	11660c	12230d	12610e	12790e
13	10720a	12040bc	11730b	12100c	12040bc	12230c
14	10100a	11850b	11920bc	12230bc	12420c	12290bc
15	5580a	10910b	12170c	12350c	12730cd	13300d
16	10280a	12170b	12610bc	12920cd	12980cd	13360d
17	7270a	10790b	12790c	12790c	13040cd	13480d
18	8780a	9410b	9600bc	9660c	9470bc	9660c
19	3890a	7400b	8590b	10410c	8970bc	8910bc
20	11660a	12980bc	12290ab	13550cd	13230cd	13730d
21	8720a	9850c	9280b	9910c	9340b	9970c
22	11980a	12420ab	11920a	12670b	12420ab	12670b

[†] Yields within a row for each site are not significantly different when followed by the same letter ($p \leq 0.10$).

Table 8. Nitrogen application and corn grain yield summary for all 22 sites.

N Application Treatment	Mean[†] Total N Applied	Number of Sites with In-season N Applied	Mean Yield
	kg N ha^{-1}	n	kg ha^{-1}
0	0		8870a[‡]
67	67		11250b
67+	131	21	11750c
134	134		12340d
134+	144	6	12340d
268	268		12590e

[†] Sum of PRE N rate and in-season N rate, averaged across all sites.

[‡] Yields within a row for each site are not significantly different when followed by the same letter ($p \leq 0.10$).

Table 9. Economic return comparison between N application strategies.

N Application Treatment Comparisons[†]	N Application Rate Increase	Yield Gain/Loss[‡]	N Cost Increase[‡]	Income Gain/Loss	Net Return Change
	kg N ha^{-1}	kg ha^{-1}	----------	$ ha^{-1}	----------
67 pre vs. 67+	64	500	45.33	45.00	(0.33)
134 pre vs. 134+	10	0	7.48	0.00	(7.48)
67 pre vs. 134 pre	67	1090	44.22	98.10	53.88
67+ vs. 134 pre	3	590	(5.73)	53.10	58.83

[†] Calculations compare the change in values by subtracting the first listed treatment from the second.

[‡] Calculations use a corn price of \$0.09 kg^{-1}, \$0.66 kg^{-1} N and an application charge of \$3.24 ha^{-1}.

General Conclusion

Regression fit of both CM readings and RCM values with ND demonstrated the importance of normalizing CM readings to minimize variability in readings attributed to variables other than N stress and to be able to provide a calibration with fertilization rate. Results show a significant quadratic-plateau relationship between RCM values and ND ($R^2 = 0.73, p < 0.001$) for corn following soybean. The regression fit has a zero ND at a RCM value of 0.97. Continuous corn has a similar relationship between RCM and ND ($R^2 = 0.76$, $p < 0.001$), indicating the same calibration for N application rate based on RCM can be used for both rotations. The similarity in RCM values at V15 and R1 growth stages suggest that there is a period of time, rather than one critical time, to collect CM readings during the latter vegetative growth period, obtain a similar indication of plant N stress, and still possibly provide enough time for in-season N application. The calibration between RCM values and ND found in this study could be used by producers to evaluate corn N stress in-season, and adjust N rate on a field basis.

Testing the N rate calibration developed based on RCM values, along with comparing PRE and in-season sensing and application strategies, demonstrated that in-season plant N sufficiency/deficiency sensing was partially successful with both the 67+ and 134+ strategies. There was better success (based on comparison of yields) with the 134+ strategy (68% compared to 82%). Corn N stress development was found more frequently with the reduced PRE 67 kg N ha^{-1} rate than with the agronomic PRE 134 kg N ha^{-1} rate. The 67+ strategy did not attain mean yields as high as the 134 PRE N or 134+ strategies. Economic return indicated that the PRE application rate of 134 kg N ha^{-1}, with affirmation of additional N need through plant N stress sensing, appears to be a more desirable strategy than using a reduced PRE N rate. Further research needs to be done with the calibration, exploring earlier sensing and N application timing for growing conditions in Iowa.

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Appendix

Table 1a. Effect of PRE + in-season N applications on average relative chlorophyll meter (RCM) value in the field-length treatment strips before in-season N application.

	Stage	N Application Treatment					
Site	Growth[†]	None	67	67	134	134	268
		RCM[‡] Value					
1	V15	0.90	0.97	0.96	0.97	0.98	1.00
2	V15	0.57	0.86	0.85	0.92	0.95	1.00
3	VT	0.88	0.95	0.94	0.98	0.98	1.00
4	VT	0.66	0.94	0.93	0.99	0.99	1.00
5	VT	0.83	0.95	0.96	1.03	1.01	1.00
6	V13	0.84	0.87	0.93	0.99	1.01	1.00
7	V15	0.89	0.96	0.97	0.98	0.98	1.00
8	V15	0.91	0.94	0.96	0.96	0.98	1.00
9	VT	0.76	0.89	0.91	0.98	0.94	1.00
10	V14	0.85	0.93	0.93	0.94	0.99	1.00
11	V13	0.77	0.95	0.95	0.97	0.97	1.00
12	V13	0.77	0.91	0.94	0.99	1.01	1.00
13	VT	0.88	0.95	0.96	0.99	0.99	1.00
14	VT	0.90	0.96	0.98	0.98	0.98	1.00
15	V15	0.77	0.89	0.93	0.97	0.98	1.00
16	V14	0.83	0.96	0.94	0.99	0.98	1.00
17	V13	0.81	0.89	0.89	0.99	0.95	1.00
18	V15	0.83	0.91	0.89	0.96	0.97	1.00
19	VT	0.75	0.92	0.88	1.03	1.03	1.00
20	V14	0.86	0.90	0.90	0.95	0.96	1.00
21	V15	0.82	0.95	0.92	0.95	0.92	1.00
22	VT	0.87	0.94	0.98	0.95	1.00	1.00

[†] Vegetative (V) corn growth stages designate the number of fully-developed leaves present when leaf chlorophyll meter data was collected; VT designates the tassel emergence stage.

[‡] RCM is relative chlorophyll meter value.

Table 2a. Effect of PRE + in-season N applications on average relative chlorophyll meter (RCM) value in the field-length treatment strips after in-season N application.

Site	Stage Growth[†]	N Application Treatment					
		None	67	67+	134	134+	268
		RCM[‡] Value					
1	R2	0.75	0.94	0.93	0.93	1.00	1.00
2	R4	0.51	0.77	0.82	0.91	0.96	1.00
3	R3	0.84	0.97	0.95	0.99	0.99	1.00
4	R3	0.51	0.82	0.84	0.95	0.95	1.00
5	R3	0.76	0.88	0.95	0.98	0.97	1.00
6	R3	0.76	0.91	0.93	1.00	0.95	1.00
7	R3	0.84	0.94	0.95	0.98	0.99	1.00
8	R4	0.83	0.89	0.90	0.97	0.98	1.00
9	R3	0.59	0.83	0.86	0.94	0.94	1.00
10	R3	0.81	0.92	0.96	0.96	1.00	1.00
11	R3	0.66	0.91	0.92	0.96	0.97	1.00
12	R3	0.67	0.85	0.93	0.98	0.97	1.00
13	R3	0.78	0.89	0.95	0.96	0.99	1.00
14	R3	0.82	0.94	0.95	0.97	0.97	1.00
15	R3	0.66	0.84	0.91	0.96	0.95	1.00
16	R3	0.73	0.92	0.90	0.96	0.99	1.00
17	R3	0.67	0.84	0.95	0.98	0.96	1.00
18	R3	0.88	0.94	1.02	0.97	1.00	1.00
19	R3	0.63	0.92	0.98	0.98	0.98	1.00
20	R3	0.92	0.93	0.99	1.00	1.01	1.00
21	R3	0.87	0.93	0.99	0.96	0.92	1.00
22	R4	0.85	0.95	0.96	0.96	0.96	1.00

[†] Reproductive (R) corn growth stages designate the stage of reproductive grain development when "late" leaf chlorophyll meter data was collected.

[‡] RCM is relative chlorophyll meter value.