Nitrogen Recommendations for Corn: An On-The-Go Sensor Compared with Current Recommendation Methods

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ABSTRACT

Precision agriculture technologies provide the capability to spatially vary N fertilizer applied to corn (Zea mays L.), potentially improving N use efficiency. The focus of this study was to evaluate the potential of improving N recommendations based on crop canopy reflectance. Corn was grown at four field sites in each of 2 yr in Centre County, Pennsylvania. Preplant treatments included: zero fertilizer, 56 kg N ha\(^{-1}\), and manure. Split-plot treatments included the following N sidedress rates as NH\(_4\)NO\(_3\): 0, 22, 45, 90, 135, 180, and 280 kg N ha\(^{-1}\), and one at-planting N rate of 280 kg N ha\(^{-1}\). Light energy reflectance (590 and 880 nm), chlorophyll meter (SPAD) measurements, and the presidedress NO\(_3\) test (PSNT) results were obtained at sidedress. The late-season stalk NO\(_3\) (LSSN) test was determined. The economic optimum nitrogen rate (EONR) was determined based on grain yield response to sidedress N rates. Relative green normalized difference vegetation index (GNDVI) and relative SPAD were based on relative measurements from the zero sidedress treatment to the 280 kg N ha\(^{-1}\) at-planting treatment. The EONR from 24 preplant treatment–site combinations was related to relative GNDVI and relative SPAD were based on relative measurements from the zero sidedress treatment to the 280 kg N ha\(^{-1}\) at-planting treatment. The EONR from 24 preplant treatment–site combinations was related to relative GNDVI (\(R^2 = 0.76\)), the PSNT (\(R^2 = 0.78\)), relative SPAD (\(R^2 = 0.72\)), and the LSSN test (\(R^2 = 0.64\)), suggesting that relative GNDVI was as good an indicator of EONR as these other, more conventional tests. Because relative GNDVI can be obtained simultaneously with a sidedress N fertilizer application, the potential to accommodate within-field spatial and season-to-season temporal variability in N availability should improve N management decisions for corn production.

The goal of N management for crops should be to apply enough N fertilizer for the producer to receive maximum return on N fertilizer inputs without unduly increasing N losses to the environment, usually as NO\(_3\) leaching to groundwater. This goal for corn production is especially important because the EONR for corn is usually larger than most other crops, and N applied in excess of the EONR linearly increases postharvest soil NO\(_3\) (Hong et al., 2007), which is susceptible to leaching losses during the fallow period. Several methods generally available to producers for making or adjusting N recommendations for corn include: the preplant NO\(_3\) test (PPNT), the PSNT, a SPAD, and a LSSN test. The PPNT is based on soil samples collected before planting. A N fertilizer recommendation is then determined based on the soil NO\(_3\) level at the beginning of the growing season, previous crop, manure, and fertilizer management practices, and expected corn yield for the current growing season. While the PPNT could be employed spatially within a field based on multiple soil samples, this test is usually implemented with a field- or farm-specific recommendation. Nitrogen recommendations following this approach have been developed based on yield response studies conducted throughout a broad geographic region (e.g., a state). The average response is then used to make a N recommendation for individual fields. In Pennsylvania, a preplant N recommendation for corn is determined without the PPNT (Beegle, 2008), relying on the other management-specific independent variables.

The PSNT should improve N management compared with the PPNT because the N recommendation is based on soil samples collected during the early growing season from the field in question (Magdoff et al., 1984; Andraski and Bundy, 2002). Early-season N mineralization from soil organic matter and plant residues will influence N availability to the crop, thus the PSNT, after some in-season mineralization has occurred, should result in a better N recommendation compared with the PPNT. While field-specific N recommendations based on the PSNT should be better than those based on the PPNT, several shortcomings with this test prevent widespread adoption. One critical consideration is that there is a short time period between when the soil samples are collected and when the crop is too tall for application of N fertilizer by traditional equipment. If inclement weather prevents N application during this time, the corn may grow beyond a stage where traditional equipment can treat the crop, either because the crop is too tall...
or a N application would simply no longer benefit the crop. In addition, spatially dense soil sampling for a variable N application would require considerable labor and analytical expenses, so the PSNT is not conducive to variable N applications.

Collecting soil samples for the PSNT and obtaining lab results are labor and time consuming; however, the SPAD is a tool that provides an indirect measure of plant chlorophyll, which is an in-season estimate of soil N supply and is quicker and easier than soil sampling. A considerable amount of research evaluating the SPAD test has been done in Pennsylvania (Piekielek and Fox, 1992; Piekielek et al., 1995), which contributed to the development of a N recommendation for corn based on the SPAD (Beegle et al., 2008).

A SPAD used to measure the greenness of the corn crop early in the growing season may have advantages over the PSNT because results from this test are immediately obtained by the corn grower, omitting the time and costs associated with soil sampling and analysis. The calculation behind a SPAD-based N recommendation usually relies on an area of the field that has received sufficient N fertilizer, which provides a relative assessment to the larger part of the field where N is still required (Varvel et al., 1997; Beegle et al., 2008). The SPAD provides a relatively rapid in-season assessment of N availability to corn from which to make a N fertilizer recommendation. One shortcoming is that the SPAD measurements are collected by hand and for specific plants, which is not conducive to making spatially variable N recommendations within a field.

The LSSN test proposed by Binford et al. (1990) is an end-of-season tool with which to evaluate the success of N fertilizer applications that occurred before or during the growing season, so N fertilizer adjustments can only be considered for subsequent cropping seasons. The LSSN concentration was strongly correlated to increasing N applications for 15 site-years in the Iowa study (Binford et al., 1990), and LSSN was also indicative of relative grain yield. Current statewide (Pennsylvania) interpretations of the LSSN test (http://www.aasl.psu.edu/Corn_stalk_nitrate.html; cited 14 Nov. 2008; verified 15 Apr. 2009) are based on three broad categories: <700 mg N kg\(^{-1}\) corresponds to low N supply, 700 to 2000 mg N kg\(^{-1}\) is designated optimum, and >2000 mg N kg\(^{-1}\) indicates that N supply was excessive. While the LSSN test is an end-of-season evaluation that helps identify when N exceeded EONR, and can be important to improving a corn grower’s general approach to making N fertilizer applications, it does not help to determine the most appropriate N fertilizer rate for the current growing season.

Remote sensing has been increasingly evaluated as a tool with which to develop N recommendations for corn (Bausch and Duke, 1996; Blackmer et al., 1996; Daughtry et al., 2000). Sensors have been mounted in satellites and airplanes, representing platforms from which entire fields can be evaluated with one image. While this approach can be successfully implemented (Sripada et al., 2006), success using these platforms depends on fair weather for measuring reflectance and the employment of additional technology services (e.g., image acquisition and interpretation) not traditionally employed by corn growers.

More recently, remote sensing platforms have moved to a front-end boom of the N fertilizer applicator (Raun et al., 2002), and small active sensors have been developed that use their own active light source rather than ambient light. An independent light source from which to measure reflectance reduces the variability of incident radiation, and the use of a small platform on the N applicator provides immediate information from which a N recommendation can be determined. This type of sensor and approach also provides a measure of N availability during the growing season and can be collected on a very dense spatial scale. Recent research suggests that these sensors can be used for developing N recommendations for corn (Dellinger et al., 2008). While this latest research has correlated EONR directly to canopy reflectance \((R^2 = 0.84);\) Dellinger et al., 2008, Sripada et al., 2008), the results were based on field studies from a relatively small geographic region, and whether the developed algorithms can be extrapolated to a larger geographic region was undetermined. While this approach holds the promise of improved N recommendations with small spatial resolution, this technology has not been compared with the more conventional approaches to making N recommendations for corn, especially in the mid-Atlantic region of the United States.

Current precision agriculture technologies provide the capability to collect crop reflectance information in real time, while N fertilizer is concurrently applied, at a rate based on the real-time reflectance information. If on-the-go remote sensing can be used to develop N recommendations for corn that are just as effective (or more so) as those developed based on PSNT or relative SPAD, the expediency of a simultaneous on-the-go N assessment and application that accounts for temporally and spatially variable conditions is unparalleled by any previous standards or methods of making N recommendations. These concepts are not new (Bausch and Duke, 1996), though the technologies providing on-the-go real time capabilities have only recently reached the marketplace. However, the current challenge is in developing algorithms for N recommendations that are underpinned by sound scientific principles and accommodate the temporal and spatial resolution that can now be managed with precision agriculture technologies.

Light energy reflectance from leaf canopies have been correlated to chlorophyll levels in the plant, which is related to N concentrations in the vegetation (Thomas and Gausman, 1977; Daughtry et al., 2000). Yield estimates for a growing crop can also be determined from reflectance (Shanahan et al., 2001; Teal et al., 2006); yet, variability in optimum N requirements do not necessarily correspond to variability in grain yield (Schmidt et al., 2002, 2007; Scharf et al., 2006). While grain yield estimate is an important consideration for developing N requirements for corn, this only takes into account the N demand side of the soil-plant relationship. The N supply side of the relationship, or the amount of N that becomes available to the plant from the soil, should also be accounted for in developing a N recommendation for corn. Variability in N availability might depend on variability in soil N mineralization, organic residue mineralization, soil water content, soil temperature, and perhaps other soil characteristics. Crop response, or expected response, to additional N fertilizer is the relevant metric, and estimating this response a priori is the goal of a successful N management program.
The objective of this study was to compare the success of an active sensor in making N recommendations for corn to more conventional approaches generally used for corn production in the mid-Atlantic region.

**MATERIALS AND METHODS**

Corn was grown at four sites in both 2005 and 2006 in Centre County, Pennsylvania (40°47´38˝ N, 77°51´37˝ W). These eight site-years were selected to represent cropping and manure application histories common to the mid-Atlantic region and to provide a wide range of EONR. Previous crops included corn, soybean (Glycine max (L.) Merr.), or alfalfa (Medicago sativa L.); some management histories that included periodic manure applications; and tillage practices that were either conventional or no-till. Additional management details for each site are provided by Dellinger et al. (2008). Except for N fertilizer application, all management practices were typical corn production practices.

At each site, three whole-plot treatments were arranged in a randomized complete block design (RCBD; four blocks), including a control of 0 kg N ha\(^{-1}\), 56 kg N ha\(^{-1}\) as NH\(_4\)NO\(_3\), and 37–122 kg ha\(^{-1}\) of available N (range among fields) as dairy manure. Whole-plot treatments were broadcast within 7 d before planting. Whole plots were 36.8 m wide by 9.1 m long. Details about method of application, manure type, incorporation method, time, or rainfall are provided by Dellinger et al. (2008).

Split plots were 4.6 m wide by 9.1 m long and treatments in 2005 included 0 (control), 22, 45, 90, 135, and 180 kg N ha\(^{-1}\) applied at V6–V7 (Ritchie et al., 1989). An additional split-plot treatment was 280 kg N ha\(^{-1}\) applied immediately after planting. In 2006, an eighth split-plot treatment was added; 280 kg N ha\(^{-1}\) applied at V6–V7. Nitrogen was broadcast applied by hand between the rows as NH\(_4\)NO\(_3\).

Preplant N recommendations for each site were determined following the approach used by The Pennsylvania State University Agricultural Analytical Service Lab (AASL) and were based on expected yield and adjusted for current and previous manure applications and previous legume crop (Beegle, 2008). Expected yield was determined as the greatest mean yield among all split-plot treatments at a given site.

Soil samples for the PPNT consisted of four or five 10-cm-diam. cores (open-faced auger) collected at planting from the control whole-plot treatments, at three depths (0–15, 15–30, and 30–60 cm). Samples from all four blocks were composited by depth, a subsample retained, air dried, and ground to pass a 2-mm sieve.

Soil pH, P, K, and organic matter content of preplant soil samples were determined by the AASL (http://www.aasl.psu.edu; cited 12 September 2008; verified 15 Apr. 2009). Soil pH was determined using a 1:1 soil:water ratio (Eckert and Sims, 1995). Phosphorus and K analyses were determined using the Mehlich-3 method and an inductively coupled plasma spectrophotometer (Wolf and Beegle, 1995). Organic matter content was determined by loss on ignition (Schulte, 1995).

Soil samples for the PSNT were collected at V6–V7 from each split plot control treatment to represent each preplant (whole-plot) treatment (n = 4). Samples consisted of two or six 10- or 2-cm-diam. cores (open faced-auger or step tube-type probe, respectively) from 0 to 30 cm. A subsample was retained, air dried, and ground to pass a 2-mm sieve.

To determine inorganic soil N, 10 g of soil were shaken in an Erlenmeyer flask with 50 mL of 2 M KCl for 30 min at 200 rpm, filtered through a Whatman No. 2 filter paper, and analyzed for NH\(_4\)—N and NO\(_3\)—N using flow injection analysis (QuickChem Method 10-107-04-1-A, Lachat Instruments, Milwaukee, WI).

Canopy reflectance data were collected at V6–V7 (20 June 2005 and 22 June 2006) using a Crop Circle ACS-210 sensor (Holland Scientific, Lincoln, NE). The ACS-210 measures reflectance at 590 (VIS\(_{590}\)) and 880 (NIR\(_{880}\)) nm from light emitted from a modulated polychromatic light emitting diode (LED) array, so is considered an active sensor. The sensor was mounted on a boom from a tractor approximately 60 cm above and perpendicular to the corn leaf canopy. The field of vision was about 35 cm wide at this height, oriented perpendicular to the corn row. Reflectance was measured from the length of one row in each plot (Row 3 of the 6-row split plot), providing 54 and 44 measurements per split plot in 2005 and 2006, respectively (eight and six measurements per second). A Trimble Pro XR5 global positioning system (GPS) receiver and Trimble TSCe field computer (Trimble Navigation Limited, Sunnyvale, CA) were used to simultaneously record the location of each reflectance measurement. All reflectance measurements outside a 1-m buffer inside the split plot boundary were discarded, and the mean reflectance (n = 54 and 44) was assigned to each split plot. The green normalized vegetation index (GNDVI) was determined for each split plot based on Eq. [1] (Dellinger et al., 2008):

\[
\text{GNDVI} = \frac{\text{NIR}_{880} - \text{VIS}_{590}}{\text{NIR}_{880} + \text{VIS}_{590}} \quad [1]
\]

Relative GNDVI for each whole-plot treatment was determined based on the means (n = 4) of the control split-plot treatment and the reference (N applied at planting) split-plot treatment (280 kg N ha\(^{-1}\)) (Eq. [2]):

\[
\text{GNDVI}_{\text{relative}} = \frac{\text{GNDVI}_{\text{control}}}{\text{GNDVI}_{\text{reference}}} \quad [2]
\]

Chlorophyll meter measurements were collected using a Minolta SPAD-502 m (Minolta Corp., Ramsey, NJ) from each of the control and the at-planting 280 kg N ha\(^{-1}\) split-plot treatments (high N reference) within each preplant treatment. Measurements were taken from six population-representative plants from the center two rows of each plot when the majority of corn plants were at V6. A mean of the six measurements represented the SPAD value for each split plot. As described by Beegle et al. (2008), measurements were taken from the fifth leaf, three quarters of the leaf length from the stalk, and about 1.5 cm from the edge of the leaf. Similar to the GNDVI values, relative SPAD values were calculated from the Control and high N reference split plots. As with relative GNDVI (Eq. [2]), relative SPAD was determined for each whole-plot treatment (n = 4).

Plant samples for the LSSN test were collected at the onset of physiological maturity following the approach by Binford
et al. (1990). A 20-cm length of stalk from five plants (rows 2 and 5) of the 135 kg N ha\(^{-1}\) split-plot treatment was collected from a height 15 cm above the soil surface. The 135 kg N ha\(^{-1}\) treatment was selected for this analysis because this treatment corresponded to a typical N application for corn production in central PA. The analytical method described by Binford et al. (1992) was used with the following modifications. Stalk samples were ground to pass a 2-mm sieve. A 0.125-g subsample was placed in an Erlenmeyer flask, shaken for 30 min at 200 rpm with 50 mL of 2 \( M \) KCl, and filtered through a Whatman No. 2 filter paper. Nitrate was determined in the filtrate by flow injection analysis (QuickChem Method 10-107-04-1-A, Lachat Instruments, Milwaukee, WI).

Grain yield was determined based on the entire length (9.1 m) of the middle two rows in each split plot, harvested with a combine modified for plot work. Yield was adjusted to 155 g kg\(^{-1}\) moisture content. Estimates of corn ($157.28 Mg\(^{-1}\) or $4.00 bu\(^{-1}\)) and fertilizer ($1.32 kg\(^{-1}\) or $0.60 lb\(^{-1}\)) prices were used with the quadratic-plateau yield response functions to calculate the economic return to N fertilizer as a function of N fertilizer rate (split-plot treatment) for each preplant treatment–site combination (three preplant treatments and eight sites correspond to 24 observations for EONR). The EONR was determined as the N rate corresponding to maximum return based on these prices. If a quadratic-plateau yield response was not statistically significant (\(s = 0.05\)), the mean yield for each increasing split-plot N treatment was compared with the mean yield for all greater split-plot N treatments. This comparison of mean yields continued with each increasing split-plot N treatment until a significant difference was not detected. The smallest split-plot N treatment in this final comparison was selected as the EONR (Sripada et al., 2008).

PROC NLIN or PROC REG (SAS Institute Inc., Cary, NC) were used to fit a split-line and linear-plateau or linear regressions, respectively, for EONR as a function of various independent variables, including relative GNDVI, LSSN test, AASL N recommendation, relative SPAD, or PSNT. Data for these regressions represent the 24 observations from eight site by three whole-plot treatment combinations, 24 EONRs corresponding to mean values (\(n = 4\)) for relative GNDVI, LSSN test, relative SPAD, and PSNT. The AASL N recommendation was determined for each site by whole-plot treatment combination. The \(R^2\) for the split-line and linear-plateau regressions were determined as the \(r^2\) for a linear regression between predicted vs. observed values. A paired \(t\) test using PROC MEANS (SAS Institute, Inc., Cary, NC) was used to evaluate selected comparisons (as noted).

**RESULTS AND DISCUSSION**

The observed EONR among the 24 site–preplant treatment combinations ranged from 0 to 224 kg N ha\(^{-1}\) (Dellinger et al., 2008). At two sites where alfalfa was the previous crop, EONR was zero for all three preplant treatments. At one of the three sites where soybean was the previous crop and where there was a history of previous routine manure applications (applied to corn in a corn-soybean rotation), EONR was zero. At the other two post-soybean sites, EONR ranged from zero to 55 kg N ha\(^{-1}\), depending on the preplant treatment. At one of these latter sites, EONR was 55 kg N ha\(^{-1}\) regardless of the preplant treatment. At the other site, EONR was 49 kg N ha\(^{-1}\) for the control and manure preplant treatments, and zero for the 56 kg N ha\(^{-1}\) preplant treatment. The EONR was greatest at three sites where corn was the previous crop. Where 56 kg N ha\(^{-1}\) was applied before planting at these three sites, mean EONR was 114 kg N ha\(^{-1}\). Mean EONR for the control and manure preplant treatments at these three sites was 147 and 150 kg N ha\(^{-1}\), respectively. Additional details and interpretation of the EONR observed for these site–preplant treatments are provided by Dellinger et al. (2008); however, the observed responses were typical of central Pennsylvania.

Differences in yield responses could not be differentiated based on preplant soil conditions. Among field sites, topsoil (0–15 cm) conditions were as follows: soil pH, 5.5 to 6.5; soil P, 17 to 101 mg kg\(^{-1}\); soil K, 93 to 223 mg kg\(^{-1}\); soil NO\(_3\)–N, 7 to 17 mg kg\(^{-1}\); soil NH\(_4\)–N, 2 to 12 mg kg\(^{-1}\); and soil organic matter content, 20 to 31 mg kg\(^{-1}\). These soil characteristics are representative of corn production fields in central PA, generally representing slightly less-than-optimum to greater-than-optimum conditions for these characteristics (Beegle, 2008).

**Agricultural Analytical Services Laboratory Nitrogen Recommendation**

Nitrogen recommendations for every site–preplant treatment combination ranged from 0 to 224 kg N ha\(^{-1}\) based on the AASL’s approach. When manure was applied as a preplant treatment, EONR was greater than the AASL N recommendation in five of eight sites (Fig. 1). These corresponded to five sites where EONR was >0, and the mean discrepancy from EONR was –45 kg N ha\(^{-1}\) (\(P > t = 0.05\), \(t\) test). The availability of N from the preplant manure application must have been less than the amount estimated following AASL’s approach (Beegle, 2008). This overestimate may be in part due to the unreliability of estimating N availability in no-till, when manure is applied on the soil surface. At the three other sites, when manure was applied preplant, the mean AASL N recommendation (35 kg N ha\(^{-3}\)) was similar (\(P > t = 0.25\), \(t\) test) (Fig. 1).

![Fig. 1. Observed economic optimum nitrogen rate (EONR) as a function of The Penn State University Agricultural Analytical Service Lab (AASL) N recommendation for corn. Observations are from 24 site–preplant treatment combinations (open symbols = zero preplant N fertilizer, closed symbols = preplant manure, crossed symbols = 56 kg N ha\(^{-1}\) fertilizer preplant, dashed line = 1:1).](image-url)
strength of this relationship was not compelling (r
combinations was significant (Fig. 1, recommendation across all site and preplant treatment com-
was not applied at planting, the AASL N recommendation was
and some sites had a manure application history), and when N
168 kg N ha\(^{-1}\) discrepancy was observed at a site where corn was
relationship between EONR and maximum yield was not sig-
6.7 and 12.4 Mg ha\(^{-1}\) (Fox and Piekielek, 1995); however, the
between 67 and 212 kg N ha\(^{-1}\) and maximum yields between
other states. However, some research suggests that maximum
formula throughout Pennsylvania. This approach is not unique
to Pennsylvania (Beegle, 2008), but is common to Missouri
history of manure application, so perhaps N mineralization was
exceptionally great during this growing season.
When N fertilizer was not applied at planting, the AASL
recommendation exceeded the observed EONR in seven of
eight sites (Fig. 1). At those seven sites, the mean AASL N
recommendation was 73 kg N ha\(^{-1}\) greater than mean EONR (P
> r < 0.01, t test). Across all the management conditions of this
study (corn after corn, corn after soybean, corn after alfalfa,
and some sites had a manure application history), and when N
was not applied at planting, the AASL N recommendation was
generally greater than the observed EONR.
A linear relationship between EONR and the AASL N
recommendation across all site and preplant treatment combi-
inations was significant (Fig. 1, P > F = 0.001); however, the
strength of this relationship was not compelling (r\(^2\) = 0.38).
General N recommendations do not account for site-specific
conditions commonly found in agronomic fields; and condi-
tions such as variability in hydrologic conditions, soil organic
matter, and soil temperature can influence EONR variability
(Fox and Pickieklek, 1995; Schmidt et al., 2007).
Recommendations provided by the AASL are based on
expected yield, with adjustments for current and residual
manure N as well as previous legume crops, applying the same
formula throughout Pennsylvania. This approach is not unique
to Pennsylvania (Beegle, 2008), but is common to Missouri
(Buchholz et al., 1993), Nebraska (Shapiro et al., 2003), and
other states. However, some research suggests that maximum
yield is not a good indicator of EONR (Fox and Pickieklek,
1995; Scharf et al., 2002; Schmidt et al., 2007). For example,
an assessment of corn yield response studies in Pennsylvania
encompassing 57 site-years indicated that EONR values varied
between 67 and 212 kg N ha\(^{-1}\) and maximum yields between
6.7 and 12.4 Mg ha\(^{-1}\) (Fox and Pickieklek, 1995); however, the
relationship between EONR and maximum yield was not sig-
nificant in that study (r\(^2\) = 0.08). Additionally, producers can
exaggerate the inherent inaccuracies of these recommendations
by overestimating yield potential (Fox and Piekielek, 1995),
increasing N applications as a method of insurance against
reduced yield or against the uncertainty about the N supply
from manure and legumes, or by not adequately accounting for
N mineralization from manures or other organic sources (Roth
and Fox, 1990). This underscores the importance of developing
methods to predict and manage for the spatial variability of soil
N supply.

The AASL N recommendations in this study tended to err
toward over-recommending N. This was especially true in fields
with a history of manure application or where alfalfa was the
previous crop, perhaps attributable to the inherent uncertainty
in estimating mineralizable N found in these cropping systems,
even though adjustments were considered for such factors
(Beegle, 2008). Producers are generally unwilling to risk reduc-
tions in corn yield as a result of applying less-than-adequate N
fertilizer; thus, this is a challenge for developing adequate N
recommendations for site-specific conditions using a general-
ized state-wide approach.

Presidedress Soil Nitrate Test
The PSNT was an excellent indicator of EONR regardless
of management practices imposed in this study (R\(^2\) = 0.78;
Fig. 2A). Consistent with the current Pennsylvania PSNT
threshold (Beegle et al., 1999), which indicates in favor of a
N fertilizer application when PSNT is <21 mg kg\(^{-1}\), EONR
was >0 for 13 of the 15 preplant treatment–site combinations
when PSNT was <22 mg kg\(^{-1}\). In every instance when PSNT
was >22 mg kg\(^{-1}\), EONR was zero. However, when observed
EONR in this study is compared with the PSNT-based N recom-
endation (Beegle et al., 1999), a Pennsylvania state-wide
recommendation, the relationship (r\(^2\) = 0.48, P > F = 0.0002)
was not as strong as between EONR and PSNT (Fig. 2A, 2B).
While EONR was better correlated to the Pennsylvania PSNT
N recommendation (Fig. 2B) than the AASL general N recom-
endation (Fig. 1), reflecting an improvement in site-specific
characterization obtained from a field-specific PSNT, the
relationship between EONR and observed PSNT (Fig. 2A)
reflected the more confined spatial and temporal resolu-
tion of the current study. The split-line relationship between
EONR and PSNT was strongly significant (R\(^2\) = 0.78, P > F
< 0.0001). Regardless of the previous crop, manure application
history, or current preplant manure or fertilizer applications,
PSNT was a very good indicator of EONR for the relatively
confined spatial and temporal scales of this study. However,
results from the current study are confined to 2 yr of data from
eight sites within a relatively small geographic region—Centre
County, PA. These results emphasize the importance of obtain-
ing site-specific information in developing models for N recom-
endations. While state-wide N recommendations have been
and continue to be effective tools for making N recommenda-
tions for corn, results from this study suggest that addressing
site specificity has significant implications for developing
improved N recommendations.

Chlorophyll Meter
Similar to results observed for PSNT, there was a fairly
strong relationship between EONR and relative SPAD
(Fig. 3A, R\(^2\) = 0.72). Relative SPAD was determined as the
ratio of the control treatment to the 280 kg N ha\(^{-1}\) at-planting (split plot) treatment measurements for any whole-plot treatment; consequently, relative SPAD > 1.0 should generally indicate adequate N supply while relative SPAD < 1.0 should generally indicate less than adequate N. Beegle et al. (2008) provided a threshold for relative SPAD = 0.95, below which additional N should be applied and above which N fertilizer is not required. Using a split-line model to describe the relationship between EONR and relative SPAD, a relative SPAD = 1.04 was the threshold observed in the current study (Fig. 3A). As relative SPAD decreased from 1.04, EONR increased linearly; and relative SPAD > 1.04 corresponded with zero EONR. Relative SPAD as an indicator for EONR appeared similarly effective regardless of the preplant treatments of control, 56 kg N ha\(^{-1}\), or manure.

A comparison of EONR to N recommendations based on relative SPAD (Beegle et al., 2008) indicated that the statewide N recommendation did not account for some of the inherent characteristics of the sites in this study. While there was a linear relationship between EONR and N recommendations based on the SPAD test (Fig. 3B), the relationship \(r^2 = 0.59\) was not as convincing as the relationship between EONR and relative SPAD (Fig. 3A). Similar to results for PSNT (Fig. 2A), relative SPAD provided a fairly good estimation of EONR for the data from this study (Fig. 3A); but was less effective when considered based on the current N recommendation algorithm developed for state-wide implementation (Fig. 3B).

**Late-Season Stalk Nitrate Test**

In the current study, the LSSN test was evaluated only for the 135 kg N ha\(^{-1}\) sidedress treatment. Because EONR ranged from 0 to 220 kg N ha\(^{-1}\), the 135 kg N ha\(^{-1}\) treatment was in excess of N requirements where EONR < 135 kg N ha\(^{-1}\), and was less than N requirements where EONR > 135 kg N ha\(^{-1}\). Nitrogen in excess of EONR (i.e., 135 – EONR) was correlated to LSSN concentration in a linear-plateau relationship \((R^2 = 0.64\), excluding one outlier; Fig. 4). For the current study results, the LSSN test was almost as good an indicator of N in excess of EONR as PSNT (Fig. 2A) and relative SPAD (Fig. 3A) were indicators of EONR.

Because the statewide LSSN interpretation is divided into three broad categories: <700, 700 to 2000, and >2000 mg N kg\(^{-1}\); a comparison of the current study results to these categories will be less quantitative than the direct comparisons allowed for the statewide N recommendations based on PSNT (Fig. 2B) and relative SPAD (Fig. 3B). For LSSN = 700 mg N kg\(^{-1}\), N in excess of EONR was ~5 kg ha\(^{-1}\) based on the relationship depicted in Fig. 4, supporting the current...
statewide LSSN recommendation in identifying this critical threshold below which N likely limits grain yield. The 700 to 2000 mg N kg⁻¹ range of LSSN from the current study (Fig. 4) corresponded to N in excess of EONR ranging from –5 to 52 kg N ha⁻¹, which is consistent with the current statewide LSSN recommendation indicating that N is adequate but not excessive. Greater than 2000 mg N kg⁻¹ corresponded with the statewide LSSN recommendation that indicates applied N is in excess of that required for optimum grain yield, in the current study corresponding to 52 to 135 kg N ha⁻¹ in excess of EONR (Fig. 4). Similar to results for PSNT and relative SPAD, the LSSN test provided a relatively effective approach to evaluating the availability of N to corn. Unlike the former two tests, the LSSN only provides a post hoc evaluation of N management for the recently completed growing season.

**Crop Reflectance Using an On-The-Go Sensor**

In the current study, EONR was strongly related to relative GNDVI \((R^2 = 0.76); \text{Fig. 5A}\) in a split-line type relationship (as revised from Dellinger et al., 2008). Similar to the determination for relative SPAD, relative GNDVI was based on the ratio of the control treatment to the 280 kg N ha⁻¹ at-planting treatment for any whole-plot treatment. For relative GNDVI < 1.01, EONR increased linearly from 41 kg N ha⁻¹ to 200 kg N ha⁻¹ as relative GNDVI decreased to 0.83. For relative GNDVI > 1.01, EONR decreased linearly from 41 kg N ha⁻¹ to zero as relative GNDVI increased to more than 1.14. Relative GNDVI > 1.0, suggesting that the control treatment has as much N in the plant as the 280 kg N ha⁻¹ treatment, should generally correspond to EONR = 0; however, a linear decreasing line for relative GNDVI > 1.01 reflects a measure of uncertainty in these observations (Fig. 5A). When manure was applied or fertilizer was not applied preplant, the response corresponded very well to observations. When 56 kg N ha⁻¹ was applied preplant, the observations were slightly more scattered around this response, suggesting that the sensor did not perform quite as well when fertilizer was applied preplant. The 56 kg N ha⁻¹ applied preplant is likely sufficient in providing adequate N nutrition through the V6 growth state, when reflectance was obtained and a relative GNDVI determined. However, this relatively small amount of N applied preplant does not always translate into sufficient N for the entire growing season, so EONR > 0 sometimes corresponds to relative GNDVI similar to or >1.0. Similar results were obtained with the SPAD method when a significant amount of N fertilizer was applied at planting (Pickielek and Fox, 1992).

An evaluation of the success in this study of a statewide N recommendation based on an on-the-go active crop reflectance sensor is not possible because a statewide N recommendation is not currently available; however, the relationship between EONR and relative GNDVI \((R^2 = 0.76)\) was as strong as the relationship between EONR and either PSNT \((R^2 = 0.78)\) or relative SPAD \((R^2 = 0.72)\), the two most effective methods of currently making a N recommendation for corn. Based on the comparable success among these methods in estimating EONR, using an active crop reflectance sensor provides a very attractive approach to making N recommendations for corn because the N rate could be determined simultaneously during the N application. This approach would eliminate costs and
time constraints associated with collecting soil samples for PSNT and waiting for the completion of laboratory analyses. The spatial constraint of collecting SPAD measurements on individual plants is improved with the ability to collect reflectance readings throughout a field; and an almost 1:1 relationship between relative GNDVI and relative SPAD (Fig. 5B) indicates that these measurements were almost interchangeable for these field sites. Temporal variability is also accounted for, to some extent, using the reflectance sensor because information is collected during the growing season and as late as possible, allowing for the opportunity to apply N fertilizer that effectively contributes to a favorable crop response. Results suggest that developing N recommendations based on crop canopy reflectance should be as effective as current methods, and should increase the likelihood of accommodating adjustments for spatial and temporal variability.

The success of using crop reflectance as an indicator for N requirement will depend on a crop that exhibits a level of N stress that is indirectly proportional to the level of soil N available throughout the period of plant uptake. Two potentially complicating factors are (i) N availability might change during the growing season (i.e., after reflectance is measured), and (ii) plant uptake dramatically increases after V6, at which or shortly after which N fertilizer is usually applied (if necessary). Consequently, the date on which crop reflectance is obtained will impact the relationship between EONR and reflectance. In this study, reflectance measured at V6–V7 provided a relationship between EONR and relative GNDVI (Fig. 5, R\textsuperscript{2} = 0.76) that was as good as or better than reflectance obtained a week earlier (R\textsuperscript{2} = 0.60) or a week later (R\textsuperscript{2} = 0.52) than V6–V7 (21 June). The difference in mean relative GNDVI between all observations for EONR = 0 and EONR > 0 was greatest at V6–V7, compared with measurements collected a week earlier or a week later (Fig. 6). This suggests that reflectance obtained at V6–V7 provided the greatest opportunity to differentiate N requirements among these sites and conditions. On the later date (29 June), mean relative GNDVI for EONR = 0 decreased slightly from 1.09 to 1.04, while mean relative GNDVI for EONR > 0 remained similar. This result may be a feature of these particular field sites, where previous legume crops or manure applications likely contributed to N mineralization, so during June as the soil temperatures usually warms up in central Pennsylvania, N mineralization continued to increase in the control treatments; consequently, the difference in GNDVI between the control treatment and the 280 kg N ha\textsuperscript{-1} at-planting treatment decreased (Fig. 6) with the later sampling time.

CONCLUSIONS

The effectiveness of an active sensor that measures crop canopy reflectance at V6–V7 was compared with other traditional approaches to making N recommendations for corn. Although the geographical scope of this study was relatively limited, a wide range of management practices typical to the mid-Atlantic region were considered, including: corn following corn, alfalfa, or soybean; no-till or conventional tillage; some fields with a recent history of manure application; and preplant treatments that included manure, N fertilizer, or zero-N fertilizer. The relationship between EONR and relative GNDVI, derived from reflectance at 590 and 880 nm, indicated that the crop reflectance information could be used to derive a N fertilizer recommendation for corn that was as effective as currently used approaches, such as ASSL, PSNT, relative SPAD, or the LSSN test, in making or adjusting N recommendations for corn. The increased likelihood of accommodating within-field spatial and temporal variability with this approach makes this an attractive possibility for improving N use efficiency for corn production.

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