Will Variable-Rate Nitrogen Fertilization Using Corn Canopy Reflectance Sensing Deliver Environmental Benefits?

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Nitrogen Management

ABSTRACT

Within-field variability of corn (*Zea mays* L.) N need calls for development of precision fertilizer application strategies. One approach many are investigating is in-season canopy reflectance sensing. Justification for this strategy partly rests with the premise it will improve N use and reduce N loss from fields. The objective of this study was to determine the potential environmental benefits using corn canopy reflectance sensing for N fertilization. On 16 field-scale sites, multiple blocks of randomized N rate plots (0–235 kg N ha^{-1}) traversing fields were side-dressed between the V7 and V11 growth stages. Sensor measurements were obtained from these and adjacent N-rich reference strips at side-dressing. Environmental indicators were examined at the determined optimal nitrogen rate ($N_{optimal}$) and the nitrogen rate the producer used ($N_{producer}$). A partial nitrogen mass balance (PNB) on response blocks within fields highlighted how variable $N_{optimal}$ likely resulted in multiple and different N loss pathways. For many fields, $N_{optimal}$ was less than $N_{producer}$, and the observed trends were as expected: higher yield efficiency (YE), higher nitrogen fertilizer recovery efficiency (NFRE), lower unaccounted for N, and less postharvest inorganic N. For a measurement examining canopy sensor-based N applications, N savings of 10 to 50 kg N ha^{-1} would be expected, but savings varied by reflectance readings, soil type, and fertilizer and grain prices. In some situations sensor-based N would be greater than $N_{producer}$. Given that sensor information can be processed into an N rate that approximates $N_{optimal}$, the results support sensor-based N applications have potential for environmental benefits.

Nitrogen fertilizer is critical in crop production and is often applied uniformly at a single rate over whole fields. However, because of a variety of factors, soil N levels and crop N needs vary spatially and temporally between fields (Bundy and Andraski, 1995; Mamo et al., 2003; Schmitt and Randall, 1994) and within the same field (Mamo et al., 2003; Scharf et al., 2005). As a result of this variability of both N supply and crop N need, uniform application rates applied at field-average need will inevitably lead to underfertilization of some areas of a field, while other areas will receive excessive N fertilization (Shanahan et al., 2008). In humid environments, N fertilizer not taken up by the crop represents economic loss for producers as well as the potential for environmental impact, with nitrate contamination of ground (Power and Schepers, 1989) and surface waters (Turner and Rabalais, 1991), and N_2O emissions as a greenhouse gas (Moiser, 2008).

One strategy for addressing this variability is in-season, site-specific N fertilization that is at the $N_{optimal}$ (N rate at which optimal yield is first achieved) or the economically optimal nitrogen rate (EONR, the N rate at which the value of yield increase is equal to the cost of additional N fertilizer) (Scharf et al., 2005). The EONR is usually marginally less than $N_{optimal}$, but can vary based on the shape of the yield response to N additions and the prices used for corn and N fertilizer (Neeteson and Wadman, 1987). When fertilization is less than EONR, profit is compromised; and when fertilization exceeds EONR, profit and potentially the environment are compromised. Hong et al. (2007) evaluated residual soil nitrate levels relative to the difference from EONR for three major soils in Missouri and found that applying N rates in excess of EONR resulted in elevated residual nitrate levels. Combined across sites of this study, N application at EONR reduced postharvest residual soil nitrate by 12 kg N ha^{-1} compared with $N_{producer}$ rates. Many producers see the risk of reduced yield with underapplication of N outweighing the costs of unused applied N (Scharf et al., 2005), and therefore use insurance N applications to guard against reduced yield.

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Published in Agron. J. 102:85–95 (2010)
Published online 13 Nov. 2009
doi:10.2134/agronj2009.0115
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Abbreviations: EONR, economically optimal nitrogen rate, or the nitrogen rate at which the value of yield increase is equal to the cost of additional N fertilizer; FGR, nitrogen fertilizer cost to grain price ratio (using \$ kg^{-1} of N and grain); NFRE, nitrogen fertilizer recovery efficiency; $N_{applied}$, nitrogen rates applied as study treatments at top-dressing; N_{grain}, estimated nitrogen removed with harvested grain; $N_{optimal}$, calculated nitrogen amount at side-dressing at which optimal yield is first achieved; $N_{producer}$, nitrogen amount applied uniformly over a field by the producers in this study; PNB, partial nitrogen mass balance; SI, nitrogen sufficiency index; YE, yield efficiency.

One way that N fertilizer applications have been evaluated is through the use of fertilizer use efficiency indices. Generally, profitability for the producer will increase and environmental losses reduced as fertilizer use efficiency increases (Mamo et al., 2003). Indices have been defined in a number of different ways. Indices summarized by Bock (1984) include expressing N use efficiency as the relationship between yield and N rate (YE), yield and N recovered by the plant (physiological efficiency), and N recovered by the plant and N rate (NFRE). Though each index requires a unique interpretation, their determination is helpful when contrasting the relative differences resulting from different management strategies. The same could be said when examining variations in N efficiency because of spatial soil and landscape factors. Thus, whether testing management strategies or assessing landscape variation, higher efficiency is the goal. Variable-rate N application seeks to match N inputs with crop needs site-specifically, and thus conceptually should increase N use efficiency.

Another approach for assessing the performance of fertilizer applications is by accounting for nutrient inputs, removal, and net change within the soil-crop system, often referred to as a nutrient budget or nutrient balance analysis (Wood et al., 1991). When a comphrensive N budget is the objective, isotopic studies are typically employed, since with N the various pools and transformation pathways are so numerous. For large field-scale studies, isotopic studies are usually cost-prohibitive. Instead, N mass balance or PNB tactics can be used (Jaynes and Karlan, 2008), accounting for nutrient pools that can be most easily measured or estimated, with the remaining pooled into a category of unaccounted for nutrient. Because N loss from cropping systems can take multiple pathways (e.g., gaseous losses, nitrate leaching), PNB assessment can be an effective tool for gauging the environmental performance of fertilization strategies and/or differences associated with soil and landscape properties.

Table 1. Number of total response blocks for each field from 2004–2007 shown along with the number of response blocks included for each environmental measure evaluated for this study.

Year	Field	Total no. of response blocks	Yield efficiency, PNB, and N saved with max. economic profit	N fertilizer recovery efficiency	Profile inorganic N
			——— Number of response blocks ———		
2004	Ben	10	10	10	
2004	Cop	8	8		
2004	Die	5	5	5	3
2004	Hay	4	4		
2004	Pet	3	3		2
2004	Sch	5	5	5	2
2004	Wil	5	5		
2005	Geb1	2	2		1
2005	Lic	2	2		
2006	Ben	28	28	2	2
2006	Cop	15	15	1	1
2006	Geb2	17	17	3	3
2006	Rie	19	19	1	1
2007	Geb1	11	11		
2007	Hac	20	20		
2007	San	28	28		

Recently, active crop canopy sensors have been tested in corn to increase N fertilizer use efficiency through in-season, site-specific N application at the optimal rate (Dellinger et al., 2008; Solari et al., 2008; Kitchen et al., 2010). Active canopy reflectance technology is based on reflectance measurements discriminating plants with different color and/or biomass, relative to varying levels of N in the plant. Research has been conducted to determine algorithms that incorporate reflectance measurements to calculate optimal side-dress N application rates in corn. Dellinger et al. (2008) found a strong relationship between EONR and green NDVI for corn that had received manure or no N before side-dress applications. Kitchen et al. (2010) related $N_{optimal}$ to the ratio of visible reflectance to near infrared reflectance and found that $N_{optimal}$ rates increased as this ratio decreased on about half the fields they evaluated.

A primary related question is whether variable-rate N fertilization using corn canopy reflectance sensing may provide environmental benefits. To answer this question, additional measurements and analyses were conducted on the field studies reported in Kitchen et al. (2010). A basic premise of this additional analysis is that canopy sensing will allow for site-specific N applications closer to $N_{optimal}$ than the rate that farmers use when applying at a single rate over whole fields. Empirical relationships developed in Kitchen et al. (2010) demonstrated $N_{optimal}$ was a function of a sensor-based sufficiency index (SI) for about half the fields evaluated. The goal of this study was to assess the potential environmental benefits when using canopy reflectance sensing. To accomplish this goal, four objectives were addressed: (1) to develop a PNB [nitrogen rates applied as study treatments at top-dressing ($N_{applied}$) – estimate of nitrogen removed from the field with grain (N_{grain})] to assess N loss potential within corn production fields; (2) to compare indices of N fertilizer use (YE, NFRE, and PNB) from $N_{optimal}$ with $N_{producer}$; (3) to evaluate postharvest inorganic N at $N_{optimal}$ and $N_{producer}$; and (4) given the relationship shown between $N_{optimal}$ and sensor-based canopy measurements in Kitchen et al. (2010), determine how much less (or more) N would be applied with variable-rate sensor-based N application compared with $N_{producer}$.

MATERIALS AND METHODS

Detailed descriptions of the research fields, experimental design and treatments, canopy reflectance sensor data collection, and general information on yield response calculations for each site are provided in the companion study described in Kitchen et al. (2010).

Environmental Measurements

Environmental measurements were examined relative to $N_{optimal}$ rate for side-dressed fertilizer N. These measurements included YE, PNB, NFRE, and postharvest soil profile inorganic N (Objectives 1–3). The YE and PNB measures were obtained for all fields and all years. Due to time constraints and labor requirements, postharvest profile inorganic N and NFRE samples were only collected from selected fields during the 2004–2006 yr. A summary of measurements by field sites is presented in Table 1.

Partial Nutrient Balance to Show Within-Field Variability

A PNB relative to the side-dress N fertilization rates was calculated by multiplying dry grain yield by 0.013 kg N $(\text{kg grain})^{-1}$ to provide an N_{grain}. While higher corn grain N content values have been reported, this value was similar to that measured in grain samples for calculating NFRE on a subset of fields of this study (see next section), and is the value reported for corn grain in Voss (1993). The N_{grain} was subtracted from the amount of side-dressed $N_{applied}$, and was referred to as *N unaccounted for*. Graphically, these values were examined relative to the difference obtained by subtracting the optimal yield N rate ($N_{optimal}$), as determined in Kitchen et al. (2010), from $N_{applied}$. The result is an examination of N unaccounted for relative to the amount of N that was needed for optimal yield, and was used to address Objective 1.

A separate graphical analysis with all fields combined was used to examine a PNB relative to $N_{producer}$. For this analysis, used to help address Objective 2, $N_{optimal}$ was subtracted from N_{grain} and examined relative to the difference of $N_{optimal}$ subtracted from $N_{producer}$.

Yield Efficiency

Yield efficiency at $N_{optimal}$ and $N_{producer}$ was calculated as described in Bock (1984) as follows:

$$\text{YE} = (\text{Y}_x - \text{Y}_{\text{noN}})/\text{N}_x \qquad [1]$$

where YE is expressed in kg grain $(\text{kg N})^{-1}$; Y_x was yield at either $N_{optimal}$ or $N_{producer}$ (kg ha^{-1}); Y_{noN} was yield where no N fertilizer was applied (kg ha^{-1}); and N_x was the N rate of either $N_{optimal}$ or $N_{producer}$ (kg ha^{-1}). The Y_x for $N_{producer}$ were determined from the quadratic-plateau models described in Kitchen et al. (2010). Within each field, YE calculations were averaged from response sets to determine YE where no N was added at planting (all years), as well as where ~67 kg N ha^{-1} (producer preplant + emergence applied N) was applied at planting (2006–2007 only). Yield efficiency values calculated at $N_{optimal}$ were then compared with YE values determined the same way at $N_{producer}$.

Nitrogen Fertilizer Recovery Efficiency

After physiological maturity, six plants were randomly chosen from the center of each N rate treatment within selected response blocks. This was done for eight fields in 2004–2006 as summarized in Table 1. Corn ears were removed, and corn stalks from the six plants were bundled to minimize leaf loss and removed from the field for further processing. Stalks were weighed, ground with a small stationary flail chopper, mixed, and subsampled for moisture content measurements (dried at 24 h at 41°C). These same subsamples were ground to pass a 1-mm sieve with a Wiley Mill (Thomas Scientific, Swedesboro, NJ)[1] and subsampled for total N analysis. Grain samples were weighed and shelled with a stationary, spinning plate corn sheller. Cobs were weighed and grain subsamples were collected. Grain moisture content was determined using a GAC 2000 DICKEY-john moisture tester (DICKEY-john Corp., Auburn, IL). Grain subsamples were ground with a cyclone mill and analyzed for total N analysis.

The NFRE was calculated as described in Bock (1984) as follows:

$$\text{NFRE} = [(\text{NR}_i - \text{NR}_{\text{noN}})/\text{N}_i] \times 100 \qquad [2]$$

where NR_i was the N recovered in stalks and grain of a fertilized plot (kg ha^{-1}), NR_{noN} was the N recovered in stalks and grain of the unfertilized plot (kg ha^{-1}), and N_i was the N rate of the plot (kg ha^{-1}). This efficiency index was then related to the difference from the actual N rate and $N_{optimal}$ rate.

Postharvest Soil Profile Inorganic Nitrogen

Postharvest soil samples were sampled with a Giddings Soil Coring Machine (Giddings Machine Co., Windsor, CO) from a subset of response blocks and selected fields (Table 1). Response blocks used represented the range in soil and landscape variability of these selected fields. Four 120-cm-deep core samples (3.8 cm diam.) were taken from the center area of each plot, spaced at various distances between corn rows to avoid biasing due to row and/or fertilizer placement between rows. Each core was divided into five depths (0–15 cm, 15–30 cm, 30–60 cm, 60–90 cm, and 90–120 cm), combined by depth, and stored at 4°C. Samples were sieved at field-moisture conditions to pass through a 6-mm screen, mixed thoroughly, and then stored in a freezer at −17°C until analysis. Soil inorganic N analysis (NO_3^- and NH_4^+) was conducted using 2 *M* KCl extraction and colormetrically analyzed with a Lachat flow injection system (Lachat Instruments, Milwaukee, WI). Results were used to calculate residual soil profile inorganic N and related to the difference from $N_{optimal}$ and applied N rate. While some within-field differences were observed between response plots, the results are presented on a field-average basis relative to $N_{producer}$. Only measurements taken from response blocks with significant yield response were included.

More or Less Nitrogen Fertilizer with Canopy Sensors

In Kitchen et al. (2010) a maximized economic return was calculated from linear-plateau models and the SI of canopy reflectance sensors for the fields. SI was calculated by dividing the sensor reading from a well-fertilized N-rich reference area by the sensor readings from the response plot areas. The economic return was the marginal profit derived from corn revenue and N fertilizer costs, relative to the yield and N costs of the farmers' uniform application rates. The analysis also included the impact of fertilizer cost to corn grain price ratios (FGR; using \$ kg^{-1} of N and grain) on maximum economic return. As an extension to Kitchen et al. (2010), Objective 4 of this investigation was accomplished by calculating the amount of N needed for maximum economic return and subtracting that from $N_{producer}$ for these same fields, and was called *N Saved*. Positive values indicate the potential environmental benefit from use of the canopy sensors. Negative values indicate more N would be called for by the sensors than what the farmers used. Included with the N Saved parameter is a *Yield Gain*

[1] Mention of trade name or commercial products is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture or the University of Missouri.

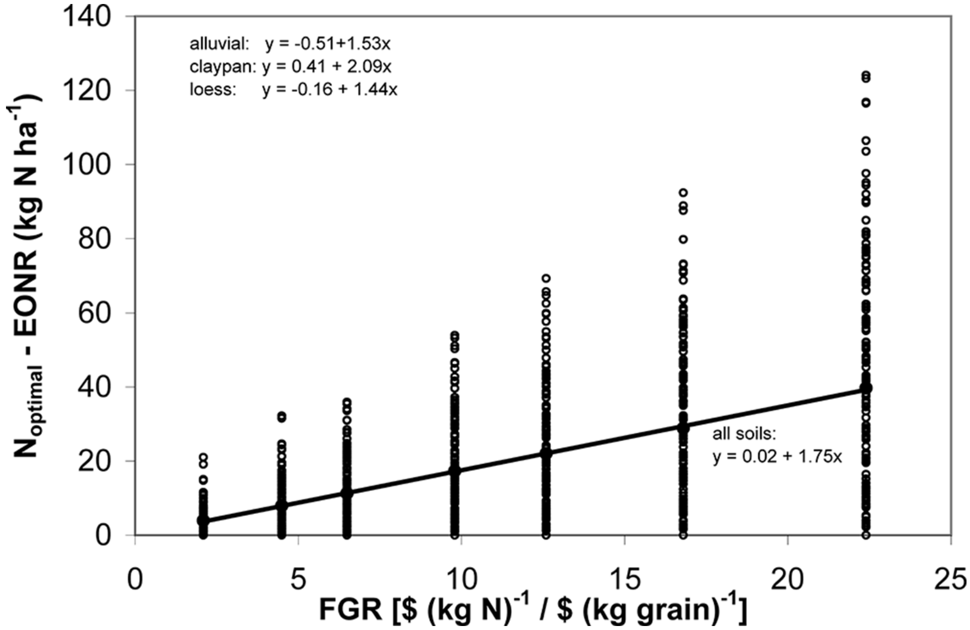

Fig. 1. The difference between $N_{optimal}$ and economically optimal nitrogen rate (EONR) was plotted at different nitrogen fertilizer cost to grain price ratio (FGR) values for the quadratic-plateau functions obtained from these studies.

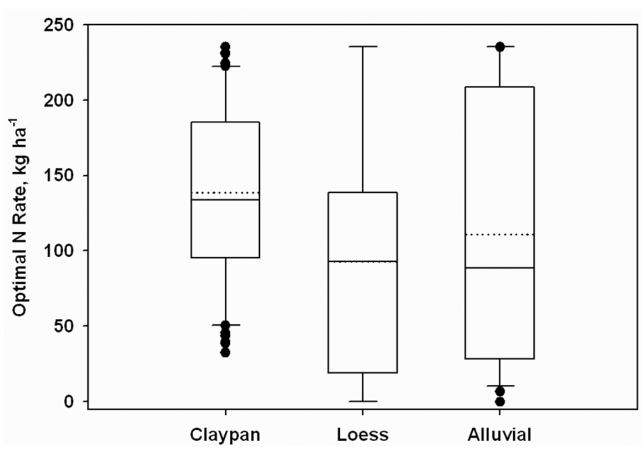

Fig. 2. Box-and-whiskers diagram of $N_{optimal}$ for claypan, loess, and alluvial soils. The lower and upper limits of each box signify the 25th and 75th percentiles of $N_{optimal}$, the lower and upper whiskers represent the 10th and 90th percentiles of $N_{optimal}$, the closed circles indicate all $N_{optimal}$ rate outliers, the horizontal line in the center of each box represents the median, and the dotted line represents the mean $N_{optimal}$.

parameter. This parameter is calculated by subtracting the yield at the maximum economic return from the yield at $N_{producer}$. Both N Saved and Yield Gain are presented relative to canopy sensor SI values for three different soil types and all soils combined.

RESULTS AND DISCUSSION

Optimal Nitrogen Compared with the Economically Optimal Nitrogen Rate

For the first three objectives of this research envirnomental measurements were examined in relation to $N_{optimal}$. This N rate parameter was used instead of a specific EONR because wide fluctuations in fertilizer N and corn grain pricing in recent years results in variable EONR values. With the possibility of ongoing uncertainties in future markets, the use of $N_{optimal}$ provided a more deterministic approach in evaluating environmental consequences of crop response to N. To illustrate the relationship between $N_{optimal}$ and EONR, their difference was plotted at various FGR values for the quadratic-plateau functions obtained from this research (Fig. 1). Differences averaged <20 kg N ha^{-1} and were generally <40 kg N ha^{-1} when FGR values were <10. This analysis was also performed separately for each of the three soil types of this study, with the corresponding regression equations shown in Fig. 1. Regression slopes were tested and the claypan soil had a significantly higher slope ($P = 0.01$) than the other two soils. The mathematical interpretation is that the quadratic parameter for claypan soil response functions was greater than for the other two soils. The agronomic interpretation is that more N fertilizer per unit of yield was required with claypan soils than the other soils. While historical U.S. prices would generally give FGR values below 10 (USDA-NASS, 2009), local- or regional-specific markets could be higher. When FGR values exceeded 10, the difference between these two magnified as illustrated, meaning that adjustments in interpretation might be warranted when FGR values are high.

Spatial Variability of Nitrogen Need

Combined across years and locations within fields, the widest range of variability in $N_{optimal}$ rate was measured in alluvial and loess soils, while the least variability was found in claypan soils (Fig. 2). At the same time, claypan soil fields had the highest mean $N_{optimal}$ rate (138 kg ha^{-1}), followed by alluvial fields (111 kg ha^{-1}), then loess fields (93 kg ha^{-1}). These compared with the mean $N_{producer}$ of 164, 194, and 202 kg ha^{-1} for claypan, alluvial, and loess soil fields, respectively (Table 2). Study fields experiencing significant water stress were omitted before analysis as described in Kitchen et al. (2010). Thus, the range in $N_{optimal}$ examined for these fields was for conditions of relatively high yield (mean = 12.6 Mg ha^{-1}). This wide range of variability in measured $N_{optimal}$ rates indicates potential benefit for field-to-field and within-field variable N application to address the changing N requirements across agricultural landscapes (Mamo et al., 2003; Scharf et al., 2005).

Within-Field Partial Nitrogen Mass Balance Variability

Nitrogen unaccounted for with grain removal was examined in relation to the difference between side-dress application rates and $N_{optimal}$ for each set of response plots of the 16 corn production fields (Fig. 3). Within each graph of Fig. 3, a line represents a set of N rate response plots. Figure 4 was developed

Table 2. Field-average yield increase at optimal N rate ($N_{optimal}$), $N_{optimal}$, and associated yield efficiency compared to the same response variables at the producer N rate ($N_{producer}$). Analysis for $N_{optimal}$ is given for either 0 or 67 kg N ha^{-1} applied at corn planting.

Year	Field	Yield Increase at $N_{optimal}$: N at planting, kg N ha^{-1} 0	67	Yield Increase at $N_{producer}$	$N_{optimal}$: N at planting, kg N ha^{-1} 0	67	$N_{producer}$	Yield Efficiency at $N_{optimal}$: N at planting, kg N ha^{-1} 0	67	Yield Efficiency at $N_{producer}$
		kg ha^{-1}			kg N ha^{-1}			kg grain (kg N)$^{-1}$		
2004	Ben	6805	–	6635	192	–	179	36.6	–	37.0
2004	Cop	8644	–	7615	222	–	157	39.0	–	48.6
2004	Die	5919	–	5746	222	–	202	27.0	–	28.5
2004	Hay	6507	–	6300	192	–	168	35.7	–	37.5
2004	Pet	1937	–	1937	94	–	202	27.9	–	9.6
2004	Sch	3575	–	3364	188	–	168	19.2	–	20.0
2004	Wil	8037	–	7387	187	–	134	43.8	–	55.0
2005	Geb1	2476	–	2391	144	–	202	20.3	–	11.9
2005	Lic	6135	–	5918	173	–	202	38.8	–	29.4
2006	Ben	5381	4253	5381	122	125	179	48.6	35.5	30.0
2006	Cop	3649	4246	3398	83	185	157	37.0	23.8	21.7
2006	Geb2	4619	741	4598	156	24	202	42.2	29.0	22.8
2006	Rie	3122	2741	3059	104	88	157	38.2	37.6	19.5
2007	Geb1	3843	240	3827	105	11	202	54.6	18.0	19.0
2007	Hac	2719	1194	2719	113	65	258	32.4	24.5	10.6
2007	San	2433	2032	2432	76	36	196	30.1	65.6	12.4

to aid in the interpretation of Fig. 3. The primary value of this PNB is to show within-field variability of unaccounted N, what the likely pools are of that unaccounted for N (described in Fig. 4), and that differences within fields are proportionate to $N_{optimal}$ variations. For many fields, unaccounted for N at $N_{optimal}$ can be quite different within fields. The range in $N_{optimal}$ for each field is represented by the variation in the *x* axis intercept. The graphs also show the relative differences associated with four different growing seasons. For 2006 and 2007, the impact of N fertilization at planting as it affects crop response to side-dress N application rates can also be examined.

For 2004, an ideal corn growing season, unaccounted for N at $N_{optimal}$ was mostly positive, ranging from ~0 to 100 kg N ha^{-1}. Compared with the other years, the sets of response plots among fields are more alike for 2004 (similar and higher $N_{optimal}$). Consequently, many of the N rates just less than $N_{optimal}$ fall into the situation where losses and transformations are believed to be mostly unavoidable (see Q2 of Fig. 4). The notable exception was the 2004 Pet field, a field that had been a well-fertilized pasture for >30 yr before being put into grain production in 2003. Seemingly high levels of N mineralization from soils of this field resulted in the average $N_{optimal}$ for this field being ~90 kg N ha^{-1} less than the average $N_{optimal}$ of the other 2004 fields. For this field, net soil N mineralization at $N_{optimal}$ (negative *y* intercept) ranged from 50 to 150 kg N ha^{-1}.

For the 2005 to 2007 growing seasons, rainfall amount and seasonal distribution were more typical and generally resulted in greater variation within fields of $N_{optimal}$, and therefore also great variation in the N unaccounted for. This contrast in growing seasons is especially noteworthy when comparing the two fields used in 2004 where the study was repeated again in 2006 (Ben and Cop fields). In 2006, $N_{optimal}$ rates from both of these fields were generally less and much more varied than in 2004, resulting in higher values of unaccounted for N for the range of fertilizer rates used. Much of that unaccounted for N, falling into Q1 of Fig. 4, was potentially nitrate N that remained in the soil after harvest. For most of the 2005–2007 fields, sets of response plots can be found that show some field areas that at N rates ≥ 168 kg N ha^{-1} (most $N_{producer}$ at or above this) would likely have unaccounted for N as nitrate N.

In 2006 and 2007, a second set of response plots was established where a total of ~67 kg N ha^{-1} was applied with spring phosphorus fertilization and/or at planting. These response plots are shown with filled symbols in the Fig. 3 graphs. For the two claypan soil fields (2006 Ben and 2006 Rie), N at planting seemed to have minimal impact on $N_{optimal}$ and unaccounted for N. For four of these seven fields (2006 Geb2, 2007 Geb1, 2007 Hac, and 2007 San), unaccounted for N was about the same, while $N_{optimal}$ rates were generally less than those plots that did not receive N at planting. Graphically this is seen as a shift to the right of the lines in the graphs. In a few cases, the reduction in $N_{optimal}$ rate averaged more than the amount of N that was applied at planting (see 2006 Geb2 and 2007 Geb1). Average reduction in $N_{optimal}$ rate for 2006 Geb2 was 129 kg N ha^{-1} and for 2007 Geb1 was 94 kg N ha^{-1}. As discussed in Kitchen et al. (2010), these two fields consisted of mollisols, soils typically with higher subsoil organic matter content than the other soils in this study. The fertilization at planting on these fields may have stimulated soil N mineralization that then helped meet most of the crop N needs so that minimal additional side-dress N was required to reach $N_{optimal}$.

Unaccounted for N on one field (2006 Cop; alluvial soils near the Missouri River), stood out as unique when contrasting the $N_{optimal}$ rate from where no N was applied at planting with treatments that received N at planting. However, this difference was a result of contrasting soils within the field where the different response plot sets were placed, and was likely not an effect of N treatments. The soil where no N was applied at planting was moderately well drained and was classified as a Nodaway silt loam. Where N was applied at planting the soil was closer to the river (slightly lower elevation), poorly drained, and was classified predominantly as Leta silty clay. Even with

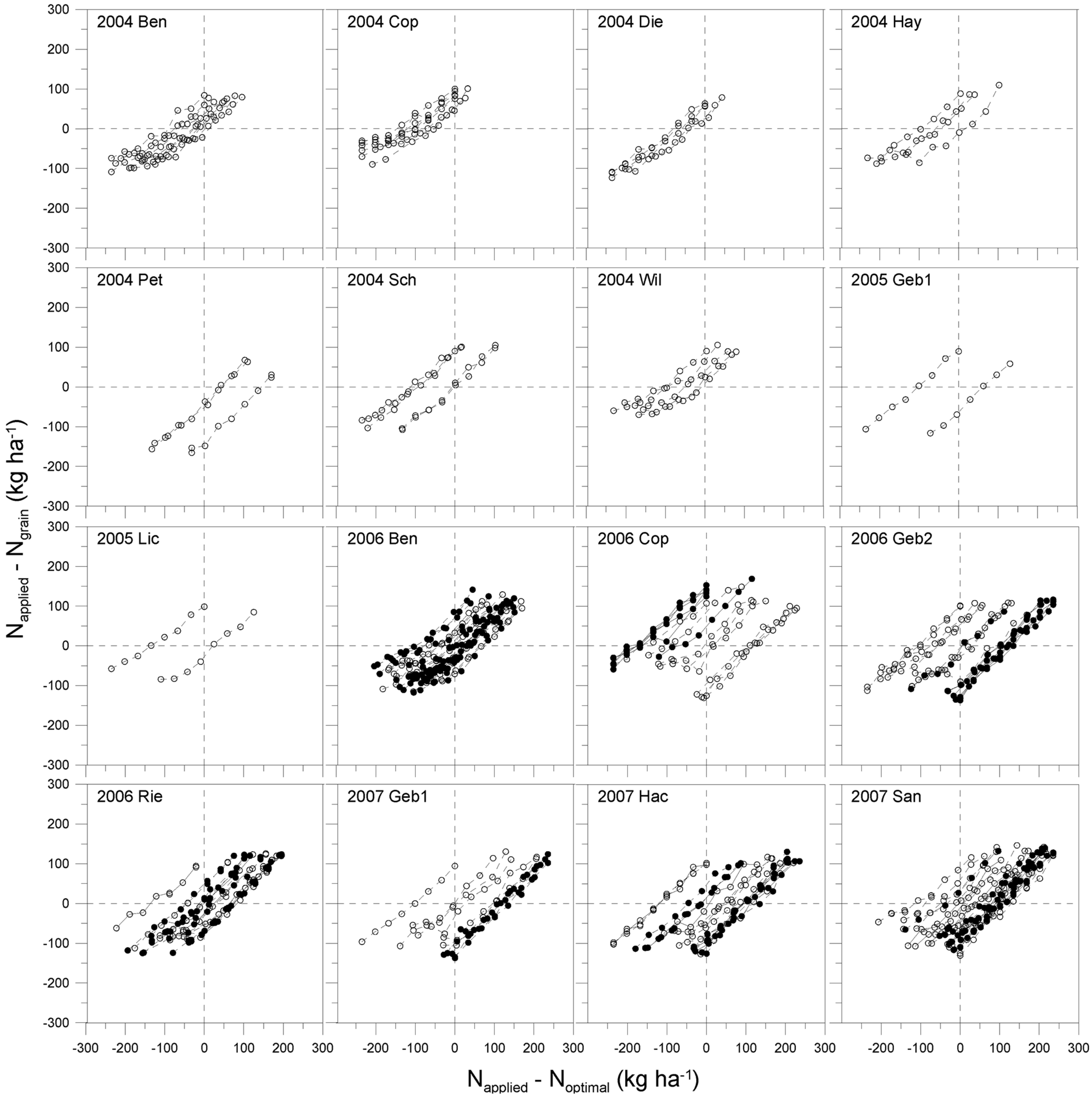

Fig. 3. A **partial nitrogen mass balance (PNB) is shown as N unaccounted for with grain removal ($N_{applied} - N_{grain}$) examined in relation to the difference between $N_{applied}$ and $N_{optimal}$. Each line connected by symbols represents one of 182 sets of response plots from the 16 corn production fields. Open symbols represent sets of response plots where no early N was applied, other than what the producer applied with preplant P fertilization (see Kitchen et al., 2010). Filled symbols represent sets of response plots where total early N was ~67 kg ha^{-1}.**

additional N applied at planting, the Leta soil required more N at side-dressing to reach $N_{optimal}$.

Yield Efficiency

Yield efficiency at $N_{optimal}$ was contrasted with $N_{producer}$ for the 16 fields (Table 2). The YE at $N_{optimal}$ generally ranged from 20 to 50 kg grain (kg N)$^{-1}$. In most instances in the 2005 to 2007 years, YE values at $N_{producer}$ were less than YE at $N_{optimal}$. We attribute this to excess N application with $N_{producer}$. In 2004, YE for $N_{producer}$ and $N_{optimal}$ were comparable for many of the fields. Fields where YE were greater for $N_{producer}$ were fields that generally needed more N than what the producers used. The field where YE was substantially less with $N_{producer}$ than $N_{optimal}$ (2004 Pet) had N fertilization by the producer significantly greater than the crop need.

Across all years and soil types, $N_{producer}$ were greater than the average of $N_{optimal}$ rate in 11 out of 16 fields. Despite $N_{producer}$ being greater for these fields, average producer yields were slightly lower in 6 of these 11 fields when compared with yields at $N_{optimal}$. This resulted in fields where $N_{producer}$ was inadequate (<$N_{optimal}$) for some areas within the field.

For claypan soils, mean YE at $N_{producer}$ [40 kg grain (kg N)$^{-1}$] was comparable with mean YE at $N_{optimal}$

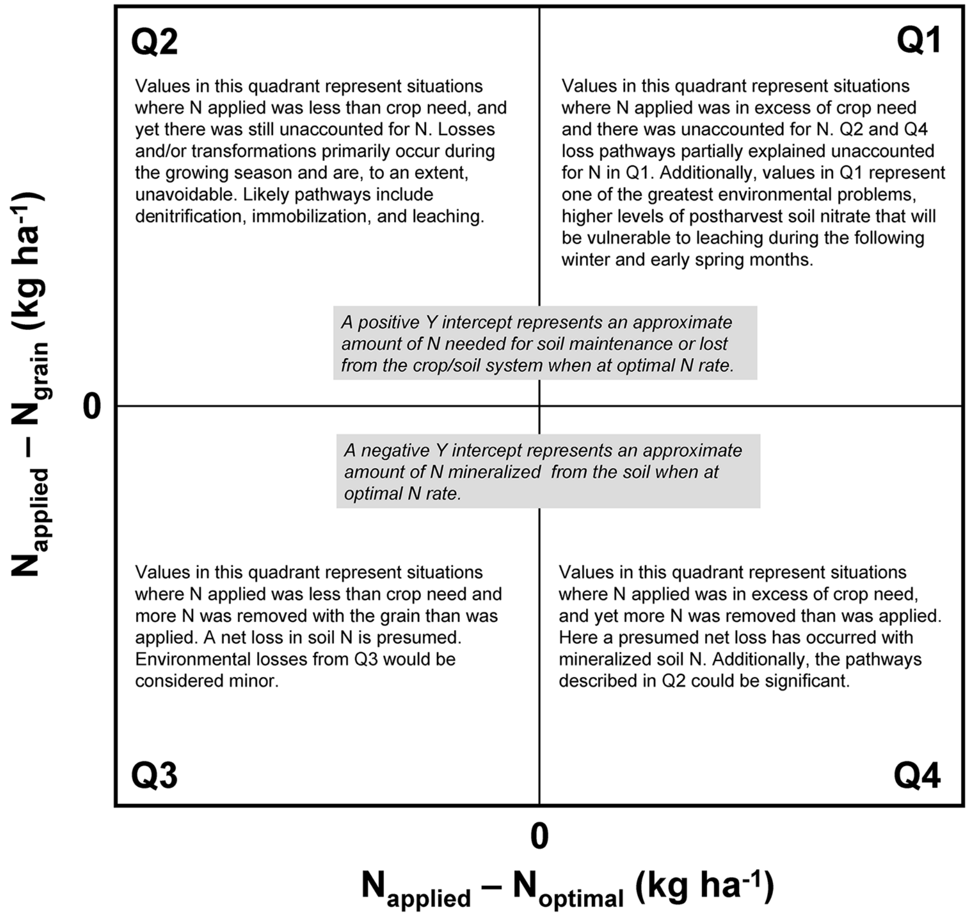

Fig. 4. An interpretation of the quadrants of the Fig. 2 PNB graphs, describing probable N fate.

[42 kg grain (kg N)$^{-1}$]. This suggests that producers at the six claypan soil fields were already efficiently managing N near $N_{optimal}$. In alluvial soils, mean YE at $N_{producer}$ [24 kg grain (kg N)$^{-1}$] was considerably lower than mean YE at the $N_{optimal}$ rate [35 kg grain (kg N)$^{-1}$]. We suspect the differences in YE to be an effect of the high spatial variability common in alluvial soils. For loess soils, mean YE at $N_{producer}$ [18 kg grain (kg N)$^{-1}$] was also substantially lower than mean YE at the $N_{optimal}$ rate [33 kg grain (kg N)$^{-1}$]. For these soils, low YE values at $N_{producer}$ were apparently the result of greater productivity soils at lower N fertilizer rates, as compared with the other soils in this study. These loess soils generally have greater topsoil depth and, as previously mentioned, have higher subsoil organic matter content than claypan and alluvial soils. Based on these findings, fertilization strategies that delineate soils contributing greater soil N and allow for adjustments to N fertilizer would likely increase the YE over $N_{producer}$ up to 15 kg grain (kg N)$^{-1}$.

Nitrogen Fertilizer Recovery Efficiency

As expected, NFRE generally decreased as N rate approached $N_{optimal}$ (Fig. 5). It is unclear why NFRE values were somewhat erratic with several of the fields. Certainly with N treatments spread over a large area within these fields (4–10 ha) we encountered larger uncontrollable errors than what others have presented for this same measurement from small plot studies (Kolberg et al., 1996). Even so, NFRE values ranged similarly to previously reported values of 30–60% (Bock, 1984; Kolberg et al., 1996). At the $N_{optimal}$ NFRE was highly variable among soil types and among fields within each soil type (Fig. 5). The NFRE ranged from 34 to 51% for claypan soils, 14 to 43% for loess soils, and 45 to 66% for alluvial soils. Even with the general decreasing trend in NFRE with increasing N rate, NFRE values for $N_{producer}$ were about the same as the NFRE at $N_{optimal}$ for most fields. In only one field (2006 Geb2) was the NFRE of $N_{producer}$ notably less (~20%) than the $N_{optimal}$ NFRE.

Producer Rates Compared Using a Partial Nitrogen Mass Balance

Figure 6 provides a combined graphical analysis of PNB for each of the 182 response blocks of this study. The N_{grain} removed at optimal yield was examined relative to $N_{producer}$. The $N_{optimal}$ was subtracted from both of these to give environmental meaning. In approximately half of the response blocks, $N_{producer}$ was greater than $N_{optimal}$ and the amount of N_{grain} at optimal yield was greater than the $N_{optimal}$ rate (both *x* and *y* values positive in Fig. 6). The interpretation of this condition is that significantly less N was needed by the crop for these field areas than the rates used by the producers. When N_{grain} removed was greater than $N_{optimal}$, we can deduce the soil provided more N than what was anticipated by producers.

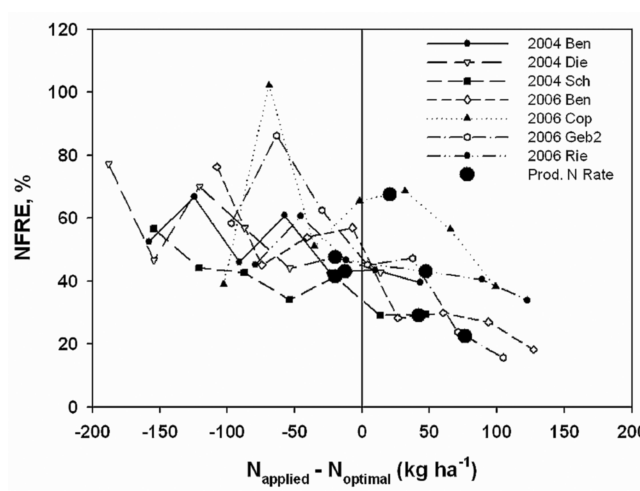

Fig. 5. Field average N fertilizer recovery efficiency (NFRE) in relation to the difference from $N_{applied}$ and $N_{optimal}$. The respective $N_{producer}$ of each field is indicated by a larger filled-circle symbol placed on the line.

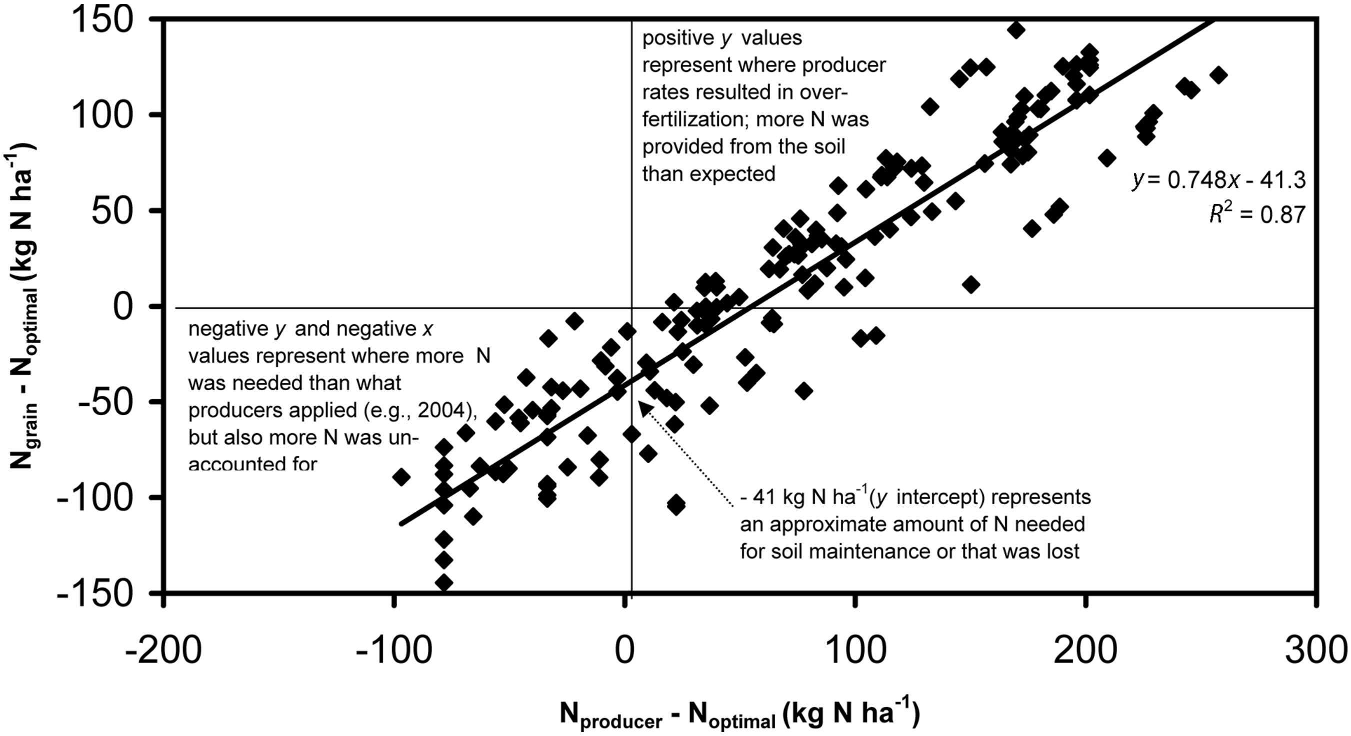

Fig. 6. A partial nitrogen mass balance (PNB) for all 182 response plots of 16 fields, where $N_{optimal}$ was subtracted from N_{grain} and examined relative to the difference of $N_{optimal}$ subtracted from $N_{producer}$.

When $N_{producer}$ and $N_{optimal}$ were equivalent, the amount of N needed for soil maintenance was ~40 kg N ha^{-1} (y intercept in Fig. 6). The ideal growing conditions of 2004 resulted in $N_{producer}$ being inadequate for optimal yield (many of the negative x and y values). Because $N_{optimal}$ was substantially greater than N_{grain} for these observations, we surmise that unaccounted for N was going to other pools/pathways (e.g., denitrification or leaching). The essence of this graph is that spatial soil and temporal weather variation create tremendous uncertainty for what $N_{optimal}$ will be. Reactive N management practices may be necessary to improve fertilizer use and leave less N unaccounted for.

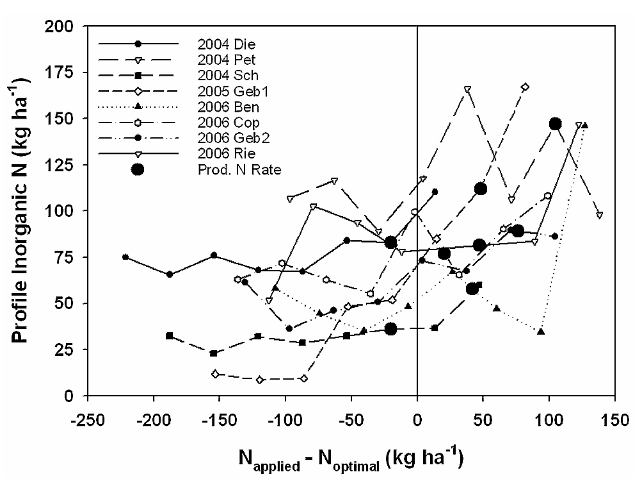

Fig. 7. Average postharvest soil profile inorganic N (nitrate + ammonium) for selected fields shown in relation to difference of $N_{optimal}$ subtracted from $N_{applied}$. The respective $N_{producer}$ of each field is indicated by a larger filled-circle symbol placed on the line.

Postharvest Soil Profile Inorganic Nitrogen

Postharvest soil profile inorganic N tended to increase as N rate increased (Fig. 7), but considerable variation was present among fields. Half the fields measured had postharvest profile N levels > 50 kg N ha^{-1} when N rates were < $N_{optimal}$. When $N_{optimal}$ and $N_{applied}$ were equivalent, profile inorganic N ranged from 36 to 79 kg ha^{-1} in claypan soils, from 71 to 114 kg ha^{-1} in loess soils, and was 99 kg ha^{-1} for the two alluvial fields. For 2004 Pet, levels of profile N were erratic, especially when N rates were in excess of the $N_{optimal}$ rate. Because this field had been managed as pasture for several previous decades, both the level of N (Carpenter-Boggs et al., 2000) and the spatial variability of N (Franzluebbers et al., 2000) might be expected to be higher for this field compared with other fields.

Profile N for some fields went up and down and did not track well in a way corresponding to N rate increases. In spite of these fluctuating values, a trend was seen when examining through regression the rate of change in N rate when either less or greater than $N_{optimal}$. Across all fields and soil types, soil profile inorganic N increased at a lower rate when N rates were < $N_{optimal}$ compared to when N rates were in excess of $N_{optimal}$ (P = 0.02). For claypan soils, when N rates were lower than $N_{optimal}$, profile inorganic N increased by 0.04 kg ha^{-1} (kg N ha^{-1} applied)$^{-1}$. When N rates were above $N_{optimal}$, this value increased to 0.49 kg ha^{-1} (kg N ha^{-1} applied)$^{-1}$ (P = 0.02). Because of erratic values with the other two soil types, rate of change when greater than or less than $N_{optimal}$ was not found significantly different from each other, but the slope values are still informative. With less than $N_{optimal}$, the average rate of increase in profile N for loess and alluvial soil fields was, respectively, 0.26 and 0.16 kg ha^{-1} (kg N ha^{-1} applied)$^{-1}$. When greater than $N_{optimal}$, the average rate of increase for loess and alluvial soil fields was, respectively, 0.66 and 0.49 kg ha^{-1} (kg N ha^{-1} applied)$^{-1}$.

Similarly, others have shown that applying N at rates > $N_{optimal}$ will increase postharvest soil N (Hong et al., 2007).

In this study, $N_{producer}$ values were greater than $N_{optimal}$ in six of eight fields (Fig. 7). However, in only two fields (2004 Pet and 2005 Geb1) did the results indicate $N_{producer}$ would produce profile N levels > 25 kg N ha^{-1} more than $N_{optimal}$.

Potential Benefits of Sensor-Based In-Season Nitrogen Application

For site-specific management technology to be adopted, it is essential to examine profitability (Swinton and Lowenberg-DeBoer, 1998). Due to volatility in current agricultural markets, producers constantly feel pressures to balance the costs of N fertilizer with corn grain price in an effort to maximize economic profitability. In consideration of these pressures, results from these 16 fields were used to empirically derive the N rates that produced the maximized economic return relative to $N_{producer}$. This was determined as a function of a canopy sensor SI (Kitchen et al., 2010). Figure 8 presents these findings in terms of the N fertilizer saved for the three major soils of this study, as well as combined across all fields. The analysis generally showed that when sensor SI values were <0.8, relatively more N fertilizer was called for, and therefore the amount of N saved diminished. Greatest N savings occurred when SI values were >0.8. This analysis also demonstrated how FGR affected the potential for saving N. When FGR was >8, the opportunity for saving N typically ranged from 50 to 100 kg N ha^{-1}. The reduction in N would cause yield loss (Fig. 8), but more profit would be made (Kitchen et al., 2010). But when FGR values were very low, N rates called for could exceed $N_{producer}$. Concurrently, yield gain would also be expected.

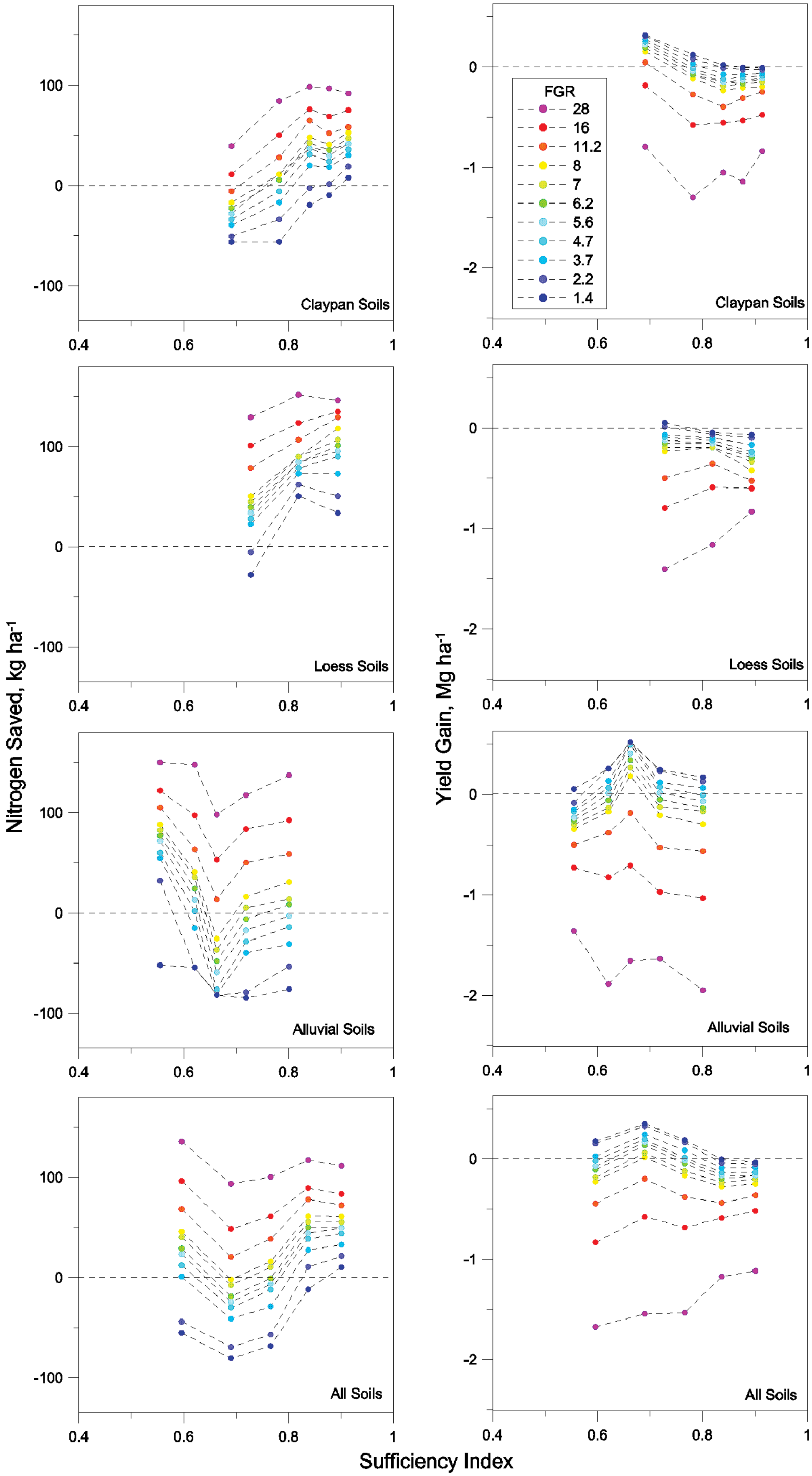

Fig. 8. Nitrogen saved and yield gain shown relative to sensor-based N sufficiency index (SI) for claypan, loess, and alluvial soils, as well as combined across all soils. These are presented with a number of different ratios of N fertilizer cost to grain price ratios (FGR), and are shown with colored dashed lines.

Table 3. Summary of primary findings from each environmental indictor.

Environmental Indicator	Primary Findings
Within-field PNB	• When N is blanket applied at one rate within fields, variance in crop N need translates into loss pathways that will vary within the same field (e.g., leaching, denitrification, immobilization) • In two of the four years (2006–2007), when N was applied at the $N_{producer}$ rate, unaccounted for N was >100 kg ha^{-1} for as least half the fields
Yield efficiency	• Yield efficiency was generally less at $N_{producer}$ than $N_{optimal}$, an outcome of excess N at the $N_{producer}$ rate for at least a portion of the fields • For productive soils with high potential of significant N mineralization during the growing season, yield efficiency at $N_{optimal}$ was almost twice that at $N_{producer}$
Nitrogen fertilizer recovery efficiency	• When at $N_{optimal}$ NFRE was highly variable between fields (ranging from about 35 to 65%) • This indicator was not very discriminating of treatment differences, likely because of the uncontrolled error associated with the measurement.
Producer rates compared using a PNB	• About half the time $N_{producer}$ was greater than $N_{optimal}$, likely because more N was available from the soil than expected • For these fields, approximately 40 kg N ha^{-1} was needed for soil maintenance
Postharvest soil profile inorganic N	• For claypan soils, soil nitrates increased when N application exceeded $N_{optimal}$. A significant trend could not be found with the other soils. • Potential errors associated with soil profile sampling made it difficult to see a consistent relationship between this indicator and N rate
Potential benefits of sensor-based in-season N application	• Opportunity for N savings relative to $N_{producer}$ was greatest when canopy sensing sufficiency index was > 0.80. • Given that sensors could be used to predict $N_{optimal}$, N fertilizer savings of 10 to 50 kg ha^{-1} could be expected on many fields

Differences were apparent among the three major soil types. For claypan soils at SI values > 0.85, results showed it would be most profitable to apply N at or below $N_{producer}$ and accept a yield loss (Fig. 8). For SI < 0.85, maximum profit would be achieved by applying more N (i.e., less N saved). In loess soils, profitability was generally maximized by applying considerably less fertilizer than $N_{producer}$. As previously discussed, $N_{optimal}$ for the loess fields of this study were often found to be less than $N_{producer}$, and therefore these fields would provide the greatest opportunity for N saved. Results from alluvial soils were unique. They not only had substantially lower SI values than both claypan and loess soil fields, but the savings was greatest at the extremes of SI values (see "V" shape in graph). At high SI values, N savings was generated because the crop needed less N than $N_{producer}$ rates. At low SI values we concluded the crop was so compromised relative to N health that side-dress N additions using sensors could not fully recover yield, and therefore less N would be recommended and N would be saved. This highlights the need for early-season N so yield is not compromised.

SUMMARY AND CONCLUSIONS

Quantifying environmental benefits of N management practices on production-scale fields is challenging. Our approach was to explore several environmental indicators of N to examine the potential of whether canopy sensor technology could help reduce the amount of N used for corn relative to what producers are currently using. In principle, reducing N fertilizer excesses will benefit the environment. Much of what was presented here compared differences in these environmental indicators as influenced by $N_{optimal}$ and $N_{producer}$. Only to the extent that canopy reflectance sensors can effectively estimate $N_{optimal}$ will these potential benefits be realized. Since $N_{producer}$ values reflected actual rates producers used on these fields during the years of this study, the comparison between $N_{optimal}$ and $N_{producer}$ offers a real expectation of the potential environmental benefit.

Table 3 summarizes the major findings by each of the environmental indicators of this research. The within-field PNB highlighted how variation in $N_{optimal}$ creates multiple and different N loss pathways and transformation scenarios. Both high levels of net soil mineralization and significant losses through leaching and/or denitrification could be occurring within these same fields. For environmental indicators where $N_{optimal}$ was less than $N_{producer}$, the observed trends were as expected: higher YE, higher NFRE, lower unaccounted for N, and less postharvest soil profile inorganic N.

The analysis that examined sensor-based N application generally found less N would be applied for many field situations. The amount of N saved varied as a function of sensor SI, soil type, and FGR. Combined over all soils and at FGR values typical in recent years (range from 4 to 9), N savings of 10 to 50 kg N ha^{-1} could be expected when canopy SI values were >0.8. Savings would be minimal for lower SI values, and in some situations sensor-based strategies would call for more N than $N_{producer}$. The potential for reducing N appeared to be especially strong for the loess soil fields of this study. Whether this result would be a general rule or is only an artifact of the loess soil fields used in this study is uncertain, and additional evaluation is necessary.

Another point is worth noting. This evaluation only examined differences between amount of N between $N_{optimal}$ and $N_{producer}$. For many of these fields, producer N applications occurred entirely before planting as opposed to N fertilization at the mid-vegetative (V7–V11) growth stage for sensor assessment and subsequent determination of $N_{optimal}$. Any efficiency gained by synchronizing N application with the growth period where N uptake was most rapid was not evaluated here, but has been documented by others (Aldrich, 1984; Fox et al., 1986; Welch et al., 1971).

This investigation supports the idea that, to the exent sensor-based N application predicts $N_{optimal}$, the amount of N typically applied for corn production can be reduced. Since the sensor-driven applications are site-specific, the reduction would undoubtedly be from areas receiving excess N when single-rate fertilization is applied over the whole field. A precondition to realizing an environmental benefit is that the sensor information can be processed by a decision-rule algorithm into an N rate that approximates $N_{optimal}$. Certainly, this study supports continued development and application of reactive reflectance sensing technologies for improved N fertilizer use in corn.

ACKNOWLEDGMENTS

We thank the producer cooperators of this research for their interest, cooperation, comments, and generosity in allowing us to work on their farms. We acknowledge Scott Drummond for his invaluable assistance in helping analyze data and developing figures. For help with equipment preparation, field work, and data collection we extend thanks to Matt Volkmann, Bob Mahurin, Kent Shannon, Kurt Holiman, Ray Benson, and Larry Mueller.

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