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Economically Optimal Nitrogen Rate Reduces Soil Residual Nitrate

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ABSTRACT

Post-harvest residual soil NO_3–N (RSN) is susceptible to transfer to water resources. Practices that minimize RSN levels can reduce N loss to the environment. Our objectives were (i) to determine if the RSN after corn (*Zea mays* L.) harvest can be reduced if N fertilizer is applied at the economically optimal N rate (EONR) as compared to current producer practices in the midwestern USA and (ii) to compare RSN levels for N fertilizer rates below, at, and above the EONR. Six experiments were conducted in producer fields in three major soil areas (Mississippi Delta alluvial, deep loess, claypan) in Missouri over 2 yr. Predominant soil great groups were Albaqualfs, Argiudolls, Haplaquolls, and Fluvaquents. At four transects in each field, six treatment N rates from 0 to 280 kg N ha^{-1} were applied, the EONR was determined, and the RSN was measured to a 0.9-m depth from five treatment plots. The EONR at sampling sites varied from 49 to 228 kg N ha^{-1} depending on site and year. Estimated average RSN at the EONR was 33 kg N ha^{-1} in the 0.9-m profile. This was at least 12 kg N ha^{-1} lower than RSN at the producers' N rates. The RSN increased with increasing ΔEONR (total N applied − EONR). This relationship was best modeled by a plateau-linear function, with a low RSN plateau at N rates well below the EONR. A linear increase in RSN began anywhere from 65 kg N ha^{-1} below the EONR to 20 kg N ha^{-1} above the EONR at the three sites with good data resolution near the EONR. Applying N rates in excess of the EONR produced elevated RSN values in all six experiments. Our results suggest that applying the EONR will produce environmental benefits in an economically sound manner, and that continued attempts to develop methods for accurately predicting EONR are justified.

Globally, application of N fertilizer has increased dramatically in recent decades and is projected as high as 165 Tg N yr^{-1} by 2050 (Galloway et al., 2004). The environmental consequences of this increase are increased losses of nitrate from soils to the environment (Matson et al., 1998). For example, nitrate leaching has contaminated well water in many areas of the midwestern USA and elsewhere in the world (Schlesinger et al., 2006). Subsurface flow and re-emergence of agricultural nitrate (including tile drains) is a major source of N loading to surface waters (Steinheimer et al., 1998) including the Mississippi River and eventually the Gulf of Mexico. This has been linked to eutrophication and chronic seasonal hypoxia on the Louisiana shelf in the northern Gulf of Mexico (Turner and Rabalais, 1991; Rabalais et al., 2002). Nitrate contamination of ground and surface waters has become a regulatory and social issue threatening crop production.

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Nitrate losses from annual row crops such as corn are greater than from perennial forages (Randall et al., 1997). Most N fertilizer in the USA, and especially in the Mississippi River basin, is applied to corn. Corn is also grown more widely on tile-drained land than other N-receiving crops, creating a rapid pathway for nitrate transport to surface waters. This makes corn the crop that loses the greatest amount of nitrate to water resources in the midwestern USA (Randall et al., 1997; Burkart and James, 1999).

Most percolation in the midwestern USA occurs during the fall/winter/spring recharge months, and this is when potential for nitrate movement out of the root zone is greatest. Timing and magnitude of nitrate movement probably vary significantly across the region due to variation in both average fall/winter/spring percolation and in periods with frozen soil. The percolated nitrate can transfer to surface waters via subsurface tile drainage or baseflow or both (Steinheimer et al., 1998). Nitrate remaining in soil after harvest (referred to as post-harvest residual soil nitrate [RSN]) is probably the main source of nitrate found in percolating water. Fertilizer N (always as ammonia) applied in the fall for the following year's corn crop can also be vulnerable, but must first convert to nitrate (a temperature-dependent process) before it can move.

Reducing nitrate movement from agricultural fields to water resources thus requires an understanding of the conditions that lead to high levels of post-harvest RSN. As fertilizer N and mineralizable soil N are the largest N pools in the Mississippi River basin (Burkart and James, 1999), the answer seemingly lies in how these two N pools are managed.

Evidence from N fertilizer response trials suggests that there is a great deal of variability in the amount of N supplied to a corn crop by the soil. High yields with no N fertilizer applied are not uncommon (Bundy and Andraski, 1995), and the amount of additional yield that can be produced due to N fertilizer is highly variable from field to field (Lory and Scharf, 2003).

This variability in soil N supply (mineralizable organic N and residual mineral N) is rarely accounted for in current N fertilizer management practices. The dominant practice for agricultural producers in the Midwest is to apply a single rate of N fertilizer over whole fields and often whole farms. Extensive research documents that crop N needs vary widely between fields (e.g., Schmitt and Randall, 1994; Scharf et al., 2005) and within fields (e.g., Blackmer and White, 1998; Scharf et al., 2005). Uniform N application rates across fields and farms

Abbreviations: CP, claypan soil region; DL, deep loess soil region; EC_a, apparent bulk soil electrical conductivity; EONR, economically optimal N rate; MD, Mississippi delta soil region; PNR, the producers' N rates; RSN, post-harvest residual soil NO_3–N; ΔEONR, the difference between total N applied and the EONR; 00, 2000; 01, 2001.

with varying N needs lead to frequent mismatches between fertilizer N applied and crop N needs. When fertilizer N plus mineralized soil N exceed crop needs, this may lead to the accumulation of RSN (Roth and Fox, 1990; Mitsch et al., 2001), which is susceptible to transfer to water resources.

During the 20th century, annual precipitation increased by 10 to 20% in the Midwest, mostly due to an increase in the number of days with heavy and very heavy precipitation events (NAST, 2001). The increase in precipitation is projected to continue across much of the region during the 21st century (NAST, 2001), so under the current N management practices the potential for nitrate losses to water resources is likely to increase.

Two important scientific syntheses have suggested that applying spatially appropriate amounts of fertilizer N can help to reduce N movement from cropping systems to water resources (Mitsch et al., 2001; Power et al., 2001). An important question in this context is, "What is the appropriate amount?" From the economic standpoint, the EONR is by definition the appropriate amount, but additional evidence is needed as to whether the EONR is the appropriate amount of N from an environmental standpoint. A few investigators have provided evidence for environmental benefits of EONR at the small-plot scale (Andraski et al., 2000; Bélanger et al., 2003). Additional research is needed to determine whether these environmental benefits can be obtained by applying EONR across variable landscapes. Our objectives were (i) to determine if RSN can be reduced if N fertilizer is applied at EONR as it varies across fields, as compared to uniform producers' N rates (PNR) in the same fields, and (ii) to compare RSN levels for N fertilizer rates below, at, and above the EONR.

MATERIALS AND METHODS

Experimental Setup

Experiments were conducted in 2000 and 2001 in three major soil areas: Mississippi Delta alluvial (MD), deep loess (DL), and claypan (CP). These are major corn production regions in Missouri. Nitrate lost to surface waters in these regions is efficiently delivered to the Gulf of Mexico (Alexander et al., 2000, Fig. 4), so agricultural production and its environmental consequences are regionally important.

Six different producers' fields (three in 2000 and three in 2001) were chosen where the row direction appeared to cross the greatest variability in soil type and landscape (Fig. 1, Table 1). Universal Transverse Mercator coordinates and experimental layouts are given in Fig. 6 and 8 of Scharf et al. (2005). All fields had been cropped to soybean [*Glycine max* (L.) Merr.] the year before the study year. Corn was planted by cooperating producers using their equipment. Planting date, hybrid, planting population, and tillage practices were selected by cooperating producers but were representative of practices used for corn production in these soil regions. The fields in the MD soil region were irrigated using center-pivot irrigation systems.

The experimental design was a randomized complete block with four replications, except for the DL site in 2000 where only three replications were used. Treatments were field-length strips of discrete N rates from 0 to 280 kg N ha^{-1} in 56-kg increments applied at the V7 growth stage (Ritchie et al., 1993), as well as 280 kg N ha^{-1} applied at V1 and two split timing treatments with part of the N applied at V1 or V7, and the remainder applied at V12. Thus, we had a total of nine treatments. Ammonium nitrate was applied between corn rows using a Gandy pneumatic metering applicator with drop tubes. Nitrogen application dates are given in Table 2.

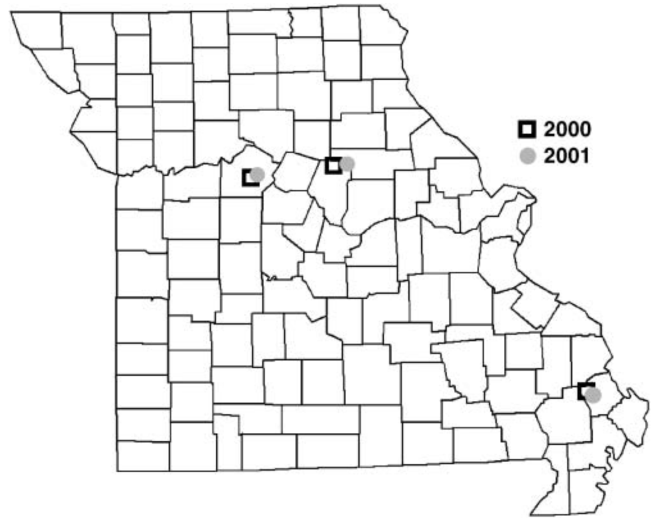

Fig. 1. Locations of the six different producers' fields in Missouri where experiments were conducted.

Daily precipitation data were obtained from the Missouri Historical Agricultural Weather Database (University of Missouri Extension, 1996). Rainfall amounts and distribution were generally favorable for corn production in 2000 and 2001 (Fig. 2).

Soil Nitrate Sampling and Analysis

Before establishing treatments, apparent bulk soil electrical conductivity (EC_a) was measured with a mobile Geonics EM-38 sensor (Geonics Limited, Mississauga, Ontario, Canada) and georeferenced with a differential global positioning system for field-length transects spaced 9 m apart. After corn harvest, four transects per field were chosen to represent a range of EC_a values. Soil EC_a was used because of its ability to delineate within-field variation in soil texture and related properties (Sudduth et al., 2005). Two transects were located in higher EC_a (finer-textured soil) areas of the field and two transects were in lower EC_a (coarser-textured) areas. Transect locations were also chosen to minimize EC_a variation within a transect. Most transects were perpendicular to crop rows, but some were placed at an angle to the rows to accommodate

Table 1. Characteristics of the six different producers' corn fields.

Year	Soil region	Soil great group predominant (secondary)	Elevation difference	Tillage	Mean yield at EONR†
			m		Mg ha^{-1}
2000	Claypan	Albaqualfs (Epiaqualfs)	2.7	chisel and disc	10.3
2000	Deep loess	Argiudolls	6.9	no-till	11.6
2000	Mississippi Delta	Fluvaquents (Epiaquerts)	1.0	chisel and disc	11.7
2001	Claypan	Albaqualfs (Epiaqualfs)	4.6	chisel and disc	8.1
2001	Deep loess	Argiudolls	5.3	no-till	13.5
2001	Mississippi Delta	Haplaquolls (Hapludalfs)	1.9	no-till	12.4

† Economically optimal N rate.

Table 2. Nitrogen fertilization application dates in the six different producers' fields.

	Corn growth stages		
Field	V1†	V7†	V12†
CP00‡	3 May 2000	7 June 2000	no application§
DL00	24 Apr. 2000	2 June 2000	19 June 2000
MD00	19 Apr. 2000	23 May 2000 1 June 2000¶	13 June 2000
CP01	3 May 2001	13 June 2001	2 July 2001
DL01	24 Apr. 2001	5 June 2001	27 June 2001
MD01	19 Apr. 2001	23 May 2001	16 June 2001

† The one-leaf (V1), seven-leaf (V7), and twelve-leaf (V12) growth stage (Ritchie et al., 1993).
‡ Abbreviation of the study fields where CP = claypan soil region, DL = deep loess soil region, MD = Mississippi delta soil region, 00 = 2000, and 01 = 2001.
§ Excessive rainfall prevented application until corn was too tall for available application equipment to be used.
¶ Rain interrupted N fertilizer application on 23 May 2000. Application was completed on 1 June 2000.

spatial patterns in EC_a. Each transect covered the nine treatment plots. Soil was sampled in five treatment plots with different N rates and times of N application: (i) the check plot where no fertilizer N was applied; (ii) the plot receiving 224 kg N ha^{-1} at V7; (iii) the plot receiving 280 kg N ha^{-1} at V7; (iv) the plot receiving 280 kg N ha^{-1} at V1, and (v) a plot receiving a treatment that varied by soil region. In the CP soil region, this treatment received 168 kg N ha^{-1} at V7, in the DL soil region it received 112 kg N ha^{-1} at V1 and 56 kg N ha^{-1} at V12, and in the MD soil region it received 168 kg N ha^{-1} at V7 and 56 kg N ha^{-1} at V12. Nitrogen rates applied by cooperating producers were closely approximated by 168 kg N ha^{-1} in the CP and DL soil regions and 224 kg N ha^{-1} in the MD soil region. The two treatment plots receiving 280 kg N ha^{-1} were sampled to determine the effects of N overapplication on RSN, and to evaluate the timing effects of N application on RSN.

At each sample site within a transect, we used a hydraulically driven probe (Giddings Machine Co., Windsor, CO) to take three soil cores to 0.9-m depth. Each of the three soil cores was sectioned into three depth increments: 0 to 30, 30 to 60, and 60 to 90 cm. We mixed each section of the three soil cores, and then air-dried at 25°C for 72 h, and crushed to pass a 2-mm sieve. Soil nitrate N concentrations were determined using a colorimetric autoanalyzer to perform cadmium reduction followed by the sulfanilamide reaction (Keeney and Nelson, 1982). Soil nitrate N concentrations were then converted to NO_3–N mass assuming a soil bulk density of 1.5 g cm^{-3}.

A total of 120 soil samples were collected (six fields × four transects per field × five plots per transect). Three RSN observations were removed from our dataset because two were missampled (global positioning system data indicated the sample location was not in the correct plot) and one had unreasonably high RSN (256 kg RSN ha^{-1} was associated with 28 kg excess fertilizer N ha^{-1} [total N applied − EONR]).

Data Analysis

Corn grain was harvested using a combine instrumented with an AL2000 grain yield monitor (AgLeader Technology, Ames, IA). A detailed description of yield monitor data collection and post-cleaning processes is given in Scharf et al. (2005). Each field was divided into cells 20-m long (in the direction of the corn rows) and 40-m wide containing all treatments. In all experimental cells where RSN was measured, N fertilizer increased corn yield. In each cell, this yield increase was modeled as a function of N fertilizer rate using a quadratic-plateau function. These functions were then used to calculate EONR values using a corn price of \$0.08 kg^{-1} and a N fertilizer price of \$0.55 kg^{-1}, which were typical prices during 2000 and 2001 (USDA, 2005a, 2005b). The EONR is the N rate at which profit is optimized. Yield at this N rate is slightly below maximum yield, but the cost of the additional fertilizer to achieve maximum yield exceeds the value of the additional yield produced. For quadratic-plateau yield response functions, EONR = [(N price/corn price)-b]/2c, where b and c are the linear and quadratic coefficients of the response function, respectively. If the soil nitrate sample transect was across the center of a cell, the EONR of that cell was used. If the transect was along the border of two or three cells, we averaged the EONR of these cells and assigned the mean to this transect. The determination, distributions, and discussion of both within-field and field-wide EONR in these six fields are detailed in Scharf et al. (2005).

The RSN content at the EONR and the PNR was estimated for each field from the relationship between the RSN content and ΔEONR. The term ΔEONR is defined as:

$$\Delta\text{EONR} = \text{total fertilizer N applied} - \text{EONR} \quad [1]$$

We fitted linear, exponential, plateau-linear, and quadratic-plateau functions to describe the RSN content response to ΔEONR. We chose these functions based on the literature, our knowledge of the relationship between the RSN content and the ΔEONR, and the shapes of the scatterplots of the RSN content vs. the ΔEONR. We assessed the goodness-of-fit of these functions based on the magnitude, randomness, and normality of the model-fit residuals. An ideal model would have the smallest residuals that exhibit a random pattern and are normally distributed. We fitted the data in SAS PROC REG (SAS Institute, 2002) for the linear function and SAS PROC NLIN (SAS Institute, 2002) for the exponential, plateau-linear, and quadratic-plateau functions. In this study, we reported all results based on the RSN content at the 0- to 0.9-m depth and mean comparisons were conducted using ANOVA or a paired t test.

RESULTS AND DISCUSSION

Economically Optimal Nitrogen Rate, Difference between Total Nitrogen Applied and Economically Optimal Nitrogen Rate, and Residual Soil Nitrate Nitrogen

The EONR at sampling sites varied widely both among and within fields (Fig. 3; Table 3). It ranged from 49 to 228 kg N ha^{-1} with a median of 154 kg N ha^{-1} and mean of 148 ± 10 (mean standard error, same hereafter) kg N ha^{-1}, respectively. This mean was 39 kg N ha^{-1} less than the mean producer N rate of 187 ± 6 kg N ha^{-1} (Table 3). The wide variability in EONR was at least partially associated with spatial variability of the soil N supply between sampling sites, as indicated by wide yield variability in the check plots (0 kg fertilizer N ha^{-1}) in these fields (data not shown). However, the reasons for variability in soil N supply are largely unknown. These fields contained some variability in soil texture and drainage, and we observed a weak trend toward higher EONR values in locations with finer soil texture or poorer drainage (data not shown). However, these factors explained a very small proportion of the total variability in EONR.

Uncertainty is inevitably associated with EONR measurements. This uncertainty is due to measurement errors (e.g., limits of yield monitor accuracy), to spatial

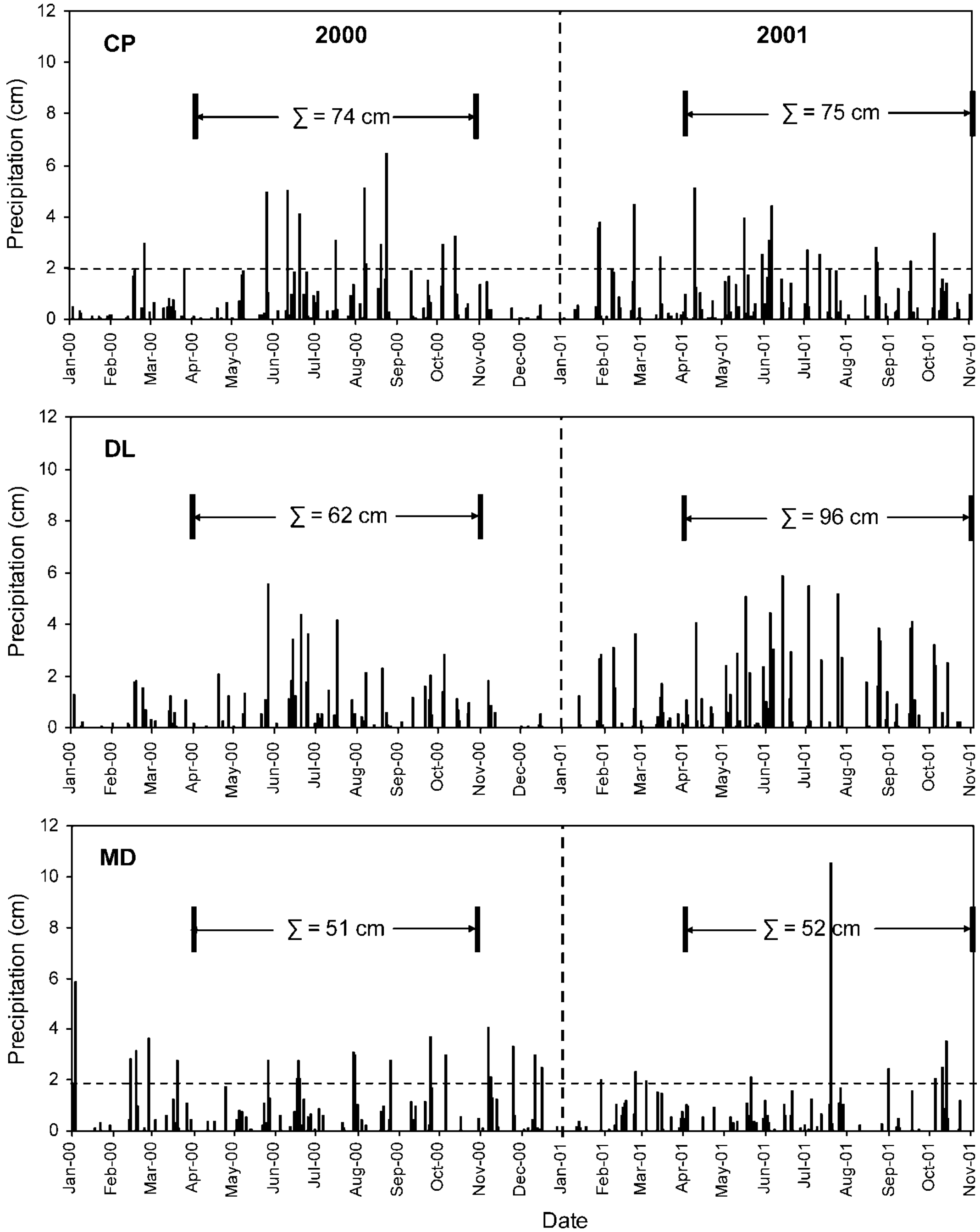

Fig. 2. Daily precipitation in 2000 and 2001 for the three soil regions (CP = claypan, DL = deep loess, MD = Mississippi delta). The symbol Σ represents the total precipitation during the study period for each region.

variation of non-treatment factors (e.g., soil water redistribution and soil organic matter content), and to spatial variability in soil N availability within the measurement area. Although there is not, to our knowledge, a sound statistical procedure available to estimate confidence intervals for our EONR estimates, we believe that the average measurement error in our EONR values is probably 10 kg N ha^{-1} Thus, the EONR values in Table 2 should be interpreted cautiously.

The ΔEONR in sampled plots ranged from −228 to 231 kg N ha^{-1} averaging 45 ± 11 kg N ha^{-1}. The ΔEONR at 84 out of the 117 sampling sites was greater than zero indicating that about 72% of sampled plots received an overapplication of fertilizer N (Fig. 4).

When averaged over all fields, average RSN in the check/unfertilized plots was 16 ± 2 kg N ha^{-1}, while it was 64 ± 5 kg N ha^{-1} in the fertilized plots. This indicates that 48 kg NO_3–N ha^{-1} associated with N applications remained in the upper 0.9 m profile after harvest. The average excess N (equal to ΔEONR) applied to the fertilized plots in the six fields was 95 ± 7 kg N ha^{-1}, so about half of the excess N was recovered as RSN. The fate of the other half of the excess N was probably divided among immobilization in soil organic matter, lux-

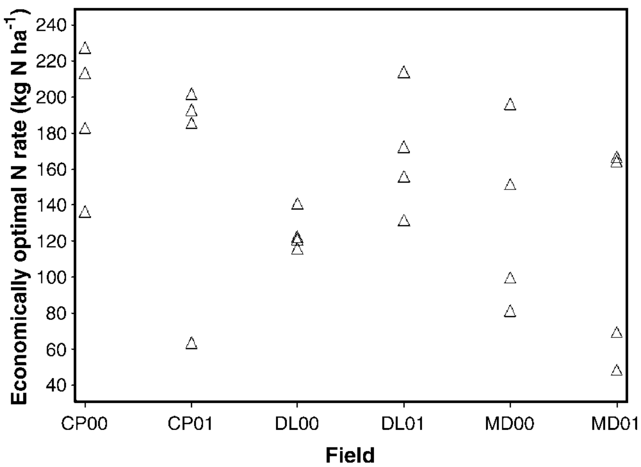

Fig. 3. Economically optimal N rate distributions for the sites where residual soil NO_3–N was sampled in the six experimental fields. In the field abbreviations on the *x* axis, CP = claypan soil region, DL = deep loess soil region, MD = Mississippi delta soil region, 00 = 2000, and 01 = 2001.

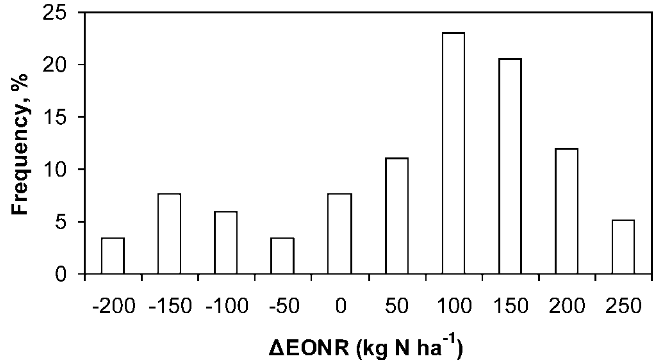

Fig. 4. The frequency distributions of the ΔEONR for the sampled treatments in six experimental fields. The ΔEONR is the difference between the total N applied and economically optimal N rate (EONR).

ury consumption of N by corn (e.g., Binford et al., 1992), NH_3 volatilization from the canopy (e.g., Sharpe and Harper, 1995), loss via denitrification, and in-season leaching to below 0.9-m depth. Uncertainties are associated with our RSN values due to differences between actual soil bulk density and the assumed value of 1.5 g cm^{-3}. Average moist bulk density values from soil surveys for the soil map units represented in this study ranged from 1.35 to 1.6 g cm^{-3}, suggesting that errors associated with this assumption would be 10% or less.

Residual Soil Nitrate Nitrogen Response to Difference between Total Nitrogen Applied and Economically Optimal Nitrogen Rate

The plateau-linear function provided the overall best description of the relationship between ΔEONR and RSN (Fig. 5), and was used to estimate the RSN content at both EONR and PNR for each field. The plateau-linear function had the lowest model-fit residuals in four of the six fields. For the MD01 (MD-2001) and CP00 (CP-2000) fields, the plateau-linear function had equivalent and 26% greater residuals, respectively, as compared to the functions with the lowest residuals. The model fitting procedure was problematic with the DL00 (DL-2000), MD00 (MD-2000), and MD01 fields. These fields had large gaps (averaging 120 kg N ha^{-1}) in the data near ΔEONR = 0, while the average gap in the other three fields with good data resolution near ΔEONR = 0 was 23 kg N ha^{-1}. The unconstrained plateau-linear models for the DL00, MD00, and MD01 fields were nearly identical to simple linear models. We felt that this was an artifact due to the data gap at these locations, given the clear plateau-linear behavior at all three locations with better data resolution. We chose to constrain the models of the DL00, MD00, and MD01 fields to have the joint point of the plateau-linear function at −65 kg N ha^{-1} because this was the lowest value observed among the three fields with good data resolution near ΔEONR = 0. Constraining the joint point in this way reduced R^2 by very little (0.010, 0.003, and 0.004 for the three fields) relative to the unconstrained models.

The RSN content in the upper 0.9-m profile tended to be related to the ΔEONR for each field, but the strength of such relationships varied among fields as reflected in R^2 and *p* values of the regression analyses (Fig. 5). The

Table 3. Comparisons of economically optimal N rates, the producers' N rates, and their corresponding post-harvest soil residual NO_3–N content in the six different producers' fields.

			Mean residual soil NO3–N with N rate equal to:			
Field	PNR†	Mean EONR‡	Zero§	PNR¶	PNR(2)#	EONR††
	kg N ha^{-1}					
CP00‡‡	168	190	8	12	14	12
DL00	168	125	25	95	78	57
MD00	224	132	23	73	68	43
CP01	168	161	12	27	21	16
DL01	168	169	12	31	33	33
MD01	224	112	14	47	58	37
Mean§§	187	148	16a	48c	45c	33b

† The producers' N rates (PNR).
‡ Economically optimal N rate (EONR).
§ Residual soil NO_3–N content in the check/unfertilized plots.
¶ Mean residual soil NO_3–N content estimated by the measured residual soil NO_3–N.
# Mean residual soil NO_3–N content estimated by the plateau-linear function.
†† Residual soil NO_3–N content estimated by the plateau-linear function.
‡‡ Abbreviation of the study fields where CP = claypan soil region, DL = deep loess soil region, MD = Mississippi delta soil region, 00 = 2000 and 01 = 2001.
§§ Mean values for residual soil nitrate N followed by different letters are significantly different (α = 0.10).

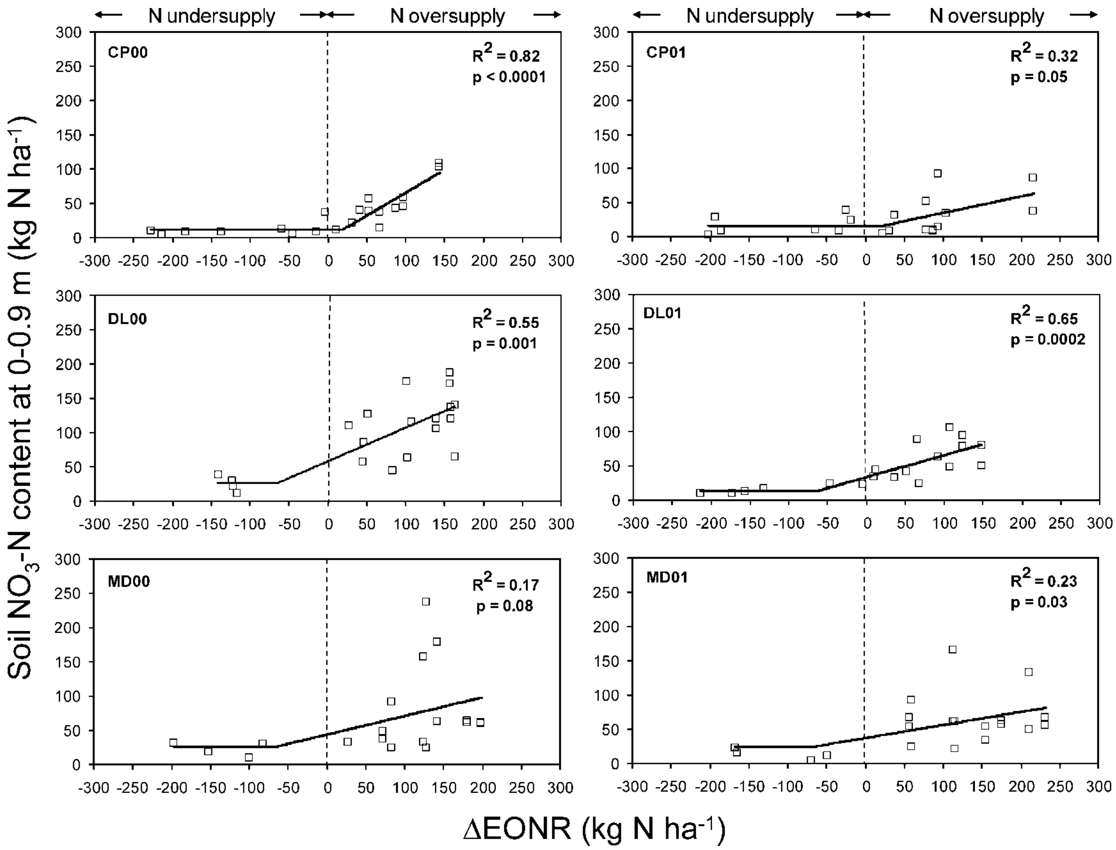

Fig. 5. Plateau-linear response functions describing the response of the post-harvest residual soil NO_3–N content within a 0.9-m depth to the ΔEONR in the six experimental fields. The ΔEONR is the difference between the total N applied and economically optimal N rate (EONR). Location abbreviations are CP = claypan soil region, DL = deep loess soil region, MD = Mississippi delta soil region, 00 = 2000, and 01 = 2001.

response of the RSN to the ΔEONR exhibited two contrast features: when ΔEONR < 0, the RSN content was lower with less variability; when ΔEONR > 0, the RSN content was higher with greater variability. Similar contrast features were observed by others (e.g., Andraski et al., 2000, Fig. 3; Bélanger et al., 2003, Fig. 2).

When averaged over all fields, the RSN content with ΔEONR < 0 ranged from 2 to 40 kg N ha^{-1} with a standard deviation of 11 kg N ha^{-1} and mean of 17 ± 2 kg N ha^{-1}. If the data from the check plots were excluded, the average RSN was 21 ± 4 kg N ha^{-1}. When ΔEONR > 0, average RSN increased to 69 ± 5 kg N ha^{-1}, indicating a direct link between excessive N inputs and NO_3–N accumulation in soil. Variability in RSN was considerable when ΔEONR > 0, ranging from 4 to 237 kg N ha^{-1} with a standard deviation of 48 kg N ha^{-1}. This greater variability is partly due to our limited sampling in that we used only three cores per sample. Because of the likely small-scale spatial variability in RSN (Ruffo et al., 2005), using a small number of subsamples might have resulted in substantial uncertainty. This is especially true when nitrate levels in soil are high. The high variability in RSN with ΔEONR > 0 creates difficulty in selecting a function to predict the RSN content based solely on the amount of excess fertilizer N. This fact is reflected by low R^2 for models of RSN as a function of ΔEONR at some locations (e.g., the fields labeled MD00 and MD01 in Fig. 5).

Residual Soil Nitrate Nitrogen Response to Difference between Total Nitrogen Applied and Economically Optimal Nitrogen Rate Classes

Figure 5 illustrates the distribution of the RSN content over ΔEONR classes, and includes ΔEONR from all transects and fields. The RSN increased with increasing ΔEONR. When ΔEONR < 0 (with N applied), average RSN was 21 ± 4 kg N ha^{-1}, and was not significantly different from that in the check plots (zero N applied). The plots of this class received an average of 174 ± 6 kg total fertilizer N ha^{-1}, which was 28 ± 7 kg N ha^{-1} less than the mean EONR for these plots. This suggests that if fertilizer N is applied at a rate below the EONR, there might be little fertilizer-derived NO_3–N in soil after harvest even if the N rate applied is high.

The RSN content at the EONR (i.e., the class labeled " = 0" in Fig. 6), estimated for each field using the plateau-linear functions shown in Fig. 5, varied from 12 to 57 with a mean of 33 ± 7 kg N ha^{-1}. This mean is well less than the 108 kg N ha^{-1} found in Wisconsin by Andraski et al. (2000, Fig. 3) for corn after corn. Part of this difference may be due to rotation. Bundy (2004) reported that RSN for corn after soybean was 37 kg N ha^{-1} at the apparent EONR (142 kg N ha^{-1}), while RSN for corn after corn was 104 kg N ha^{-1} at the apparent EONR (189 kg N ha^{-1}). All of our fields had soybean as the previous crop, and agree well with the results of Bundy (2004) for RSN at the EONR for corn following

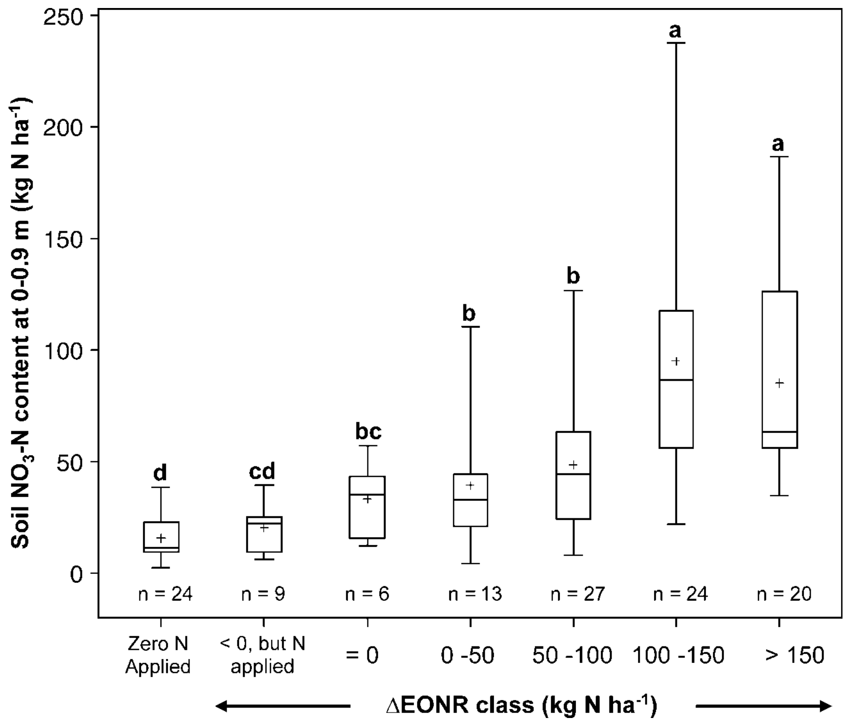

Fig. 6. Comparisons of the post-harvest residual soil NO_3–N (RSN) content for different sample classes via the box-and-whiskers diagram. The upper and lower limits of each box signify the 25th and 75th percentiles for the RSN, the horizontal line in the center of the box indicates the median, the "+" sign in each box indicates the mean, and the "whiskers" or arms represent the full range of the RSN observed in each class. The ΔEONR is the difference between the total N applied and economically optimal N rate (EONR). Different letters above the upper limits of each box indicate mean significance differences at the 0.05 probability level. The sample size of each class is given below the lower limits of each box. The class with ΔEONR = 0 contains one value from each field, which was estimated from the plateau-linear function shown in Fig. 5. All other classes consist of observations classed from individual plot samples.

soybean. Average RSN at the EONR was not significantly greater than that in the fertilized plots with ΔEONR < 0 ($p = 0.12$), but was significantly greater than that in the check plots ($p = 0.003$).

When 0 < ΔEONR < 50, average RSN increased to 39 ± 8 kg N ha^{-1}, and was significantly greater than when ΔEONR < 0 (with N applied) ($p = 0.09$), but was not significantly greater than when ΔEONR = 0 ($p = 0.64$). When 50 < ΔEONR < 100, average RSN increased to 49 ± 6 kg N ha^{-1}, and was not significantly greater than when ΔEONR = 0 ($p = 0.23$). When ΔEONR > 100, average RSN increased to 91 ± 7 kg N ha^{-1}, which was significantly greater than all groups with ΔEONR < 100 kg N ha^{-1} ($p < 0.006$). It should be noted that about 21% of the PNR plots in the six fields received more than 100 kg excess fertilizer N ha^{-1}. Consequently, such excessive RSN would mainly be found in a small proportion of the total area (i.e., "hotspots").

Comparisons of Residual Soil Nitrate Nitrogen at Economically Optimal Nitrogen Rate and Producers' Nitrogen Rate

The mean RSN content at EONR averaged over all fields was less by 12 or 15 kg N ha^{-1} (Table 3) than that at PNR (paired t test, $p = 0.04$ if the plateau-linear functions were used to estimate RSN at PNR, or $p = 0.08$ if the RSN observations were used). However, in fields where average EONR was greater than or approximately equal to the PNR (i.e., the fields CP00, CP01 [CP-2001], and DL01 [DL-2001] in Table 3), there was little difference in the RSN content associated with the two strategies. In fields where the PNR was at least 43 kg N ha^{-1} above the mean EONR (i.e., the fields DL00, MD00, and MD01), applying fertilizer N at the EONR could reduce the RSN content by 22 kg N ha^{-1} (paired t test, $p = 0.003$) if the plateau-linear functions were used or 26 kg N ha^{-1} ($p = 0.09$) if the RSN observations were used. This suggests that identifying whole fields or large portions of a field where N rates can be reduced below the current PNR without economic loss will be a beneficial first step toward reducing RSN and N loss. Additional environmental benefits may be possible by adopting variable-rate N applications.

Timing Effect of Nitrogen Application on Residual Soil Nitrate Nitrogen

Time of N fertilization influenced RSN in only two fields, but with opposite outcomes. For the CP01 field, average RSN with fertilizer N applied at V1 was significantly less by 41 kg N ha^{-1} than when fertilizer N was applied at V7 (paired t test, $p = 0.09$). The opposite trend was found in the DL01 field where average RSN with fertilizer N applied at V1 was significantly greater by 34 kg N ha^{-1} than when fertilizer N was applied at V7 (paired t test, $p = 0.10$). The opposite timing effects between the two fields might be associated with the presence of the rainfall events right before and after N applications. In the CP01 field, 3.70 cm of rain accumulated in the 5 d after N application at V1, but there was only 2.20 cm of rain in the 5 d after N application at V7 (Table 2 and Fig. 2). In the DL01 field, there was no rain at V1 until 9 d after N application. At V7, 4.45 cm of rain occurred 1 d before N application and 3.45 cm of rain accumulated in the 5 d after N application. We speculate that significant rainfall events right before and/or after N application might have increased nitrate loss via denitrification and other pathways like leaching via preferential flow, thus causing the opposite timing effects. In the CP fields, high-clay, low hydraulic conductivity subsoils result in poorly or somewhat poorly drained soils, which are vulnerable to saturation and N loss via denitrification. Jokela and Randall (1997, Table 5) reported a similar inconsistent timing effect (between N applications at planting and V8) on RSN. Weather changes and denitrification were considered as two important factors contributing to their inconsistent timing effects.

While timing effects occurred in two fields, they were opposite in direction and no consistent effect was seen. Thus, when averaged over the six fields, there were no significant differences in the RSN content between fertilizer N applied at V1 and V7 (paired *t* test, $p = 0.67$). Thus, time of application had little effect on RSN in these six fields. Nitrogen rate was a much more important determinant of RSN.

SUMMARY AND CONCLUSIONS

In a 2-yr study of six Midwestern corn fields, estimated average RSN at the EONR in the upper 0.9-m profile was 33 kg N ha^{-1}, and this was less than average RSN at the PNR. Depending on the method we used to estimate RSN at the PNR, this reduction was either 12 or 15 kg N ha^{-1}. The RSN increased with increasing ΔEONR. When $\Delta\text{EONR} < 0$, average RSN was 21 kg N ha^{-1}, and was not significantly different than if no fertilizer was applied or if fertilizer N was applied at the EONR. When $0 < \Delta\text{EONR} < 50$ kg N ha^{-1}, average RSN increased to 39 kg N ha^{-1}, but was not significantly greater than when $\Delta\text{EONR} = 0$. When $50 < \Delta\text{EONR} < 100$, average RSN increased to 49 kg N ha^{-1}, and was not significantly greater than when $\Delta\text{EONR} = 0$. When $\Delta\text{EONR} > 100$ kg N ha^{-1}, average RSN increased to 91 kg N ha^{-1}, which was significantly greater than all groups with $\Delta\text{EONR} < 100$ kg N ha^{-1}.

Applying fertilizer N at the EONR or less can achieve environmental benefits by reducing RSN. Economically optimal N rates at sampling sites varied widely both among and within these six fields, suggesting the need to accurately diagnose EONR at both whole- and sub-field scales. Increasing global N use increases the need to minimize environmental impacts of N fertilizer, and in North America increasing natural gas and fertilizer costs increase the economic need to avoid overapplication of N. Both needs can be addressed by applying the EONR. Further improvements in techniques for diagnosing EONR at the sub-field scale are justified in these production environments. These techniques might be based on crop reflectance sensors, aerial imagery, soil tests, and/or soil/landscape attributes.

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