SHOULD WE ABANDON SOIL TESTING AND YIELD GOALS IN ESTIMATING NITROGEN RATES FOR CORN?

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What Causes Variation in Optimal N rates?

If the prices of corn and fertilizer-N and the shape of the N response function relating crop yield to the amount of fertilizer used are known, calculating an economically optimal N rate (EONR) for maximizing the net return to applied N is straightforward: the EONR is the N rate at which no further increase in net return occurs. In most cropping systems and under common price scenarios, crop yield at the EONR is within 95 to 99% of the maximum yield obtained for the specific management package. In reality, EONR may vary widely among regions, fields, management zones within a field, and different growing seasons in the same field. Besides prices of corn and fertilizer, yield potential, effective N supply from soil and other indigenous sources, and fertilizer-N efficiency are the primary determinants of the EONR. However, EONR is not necessarily correlated with crop yield *per se* because absolute yield levels depend on (i) the site-specific, genetic-climatic yield potential (Yp, maximum possible yield without any limitations to crop growth) and (ii) the size of the yield gap caused by limitations due to water and other nutrients or yield losses due to pests and other causes. Both vary widely among farms and among cropping seasons in the same field.

To illustrate this, Table 1 summarizes results of recent N response trials with irrigated corn in Nebraska. These trials were mostly conducted in producers' fields, not as long-term experiments with fixed plot locations. For a detailed description of the experimental details, see Dobermann et al. (2006). Across all 28 site-years summarized in Table 1, yield potential simulated with the Hybrid-Maize model (Yang et al., 2004) ranged from 217 to 327 bu/acre. Observed maximum yields of corn following corn (CC) and corn following soybean (CS) averaged nearly 90% of the yield potential. Average maximum yields of CC were 242 bu/acre as compared to 230 bu/acre for CS. Higher CC yields in this study were due to a higher average climatic yield potential at CC sites (276 bu/acre) as compared to CS sites (260 bu/acre) locations (Table 1). At most sites, maximum measured corn yields were in the 210 to 275 bu/acre range, including 14 site-years with yields greater than 240 bu/acre.

Average yield without N application (Y_0) was 151 bu/acre in CC vs. 166 bu/acre in CS. In relative terms, Y_0 ranged from 47 to 91% of the maximum yield measured in CC and 55 to 92% in CS. At a corn ($/bu) to N ($/lb) price ratio of 10:1, average EONR was 168 lb N/acre for CC and 120 lb N/acre for CS. The difference between these two average EONR was nearly identical to the current soybean N credit of 45 lb Nacre suggested for corn in Nebraska (Shapiro et al., 2003). Average yield increase from applying N at the EONR (ΔY) was 84 bu/acre in CC as compared to 61 bu/acre in CS, which reflects the lower N supply from indigenous sources under CC as well as the higher climatic yield potential at the CC sites as compared to CS.

Table 1. Irrigated corn response to nitrogen in Nebraska, 2002 to 2004. Economically optimal N rates, associated yields and N use efficiency were obtained as averages of two different N response functions fitted to each site-year dataset (Dobermann *et al.*, 2006). Trials were conducted in different agroecological zones of Nebraska. The data set included 11 no-till sites, 8 with ridge-till and 9 with conventional tillage. Corn yield potential was simulated for each site-year with the Hybrid-Maize model (Yang et al., 2004; Yang et al., 2006).

		Corn following corn 12 site-years				Corn following soybean 16 site-years			
		Mean	SD	Min.	Max.	Mean	SD	Min.	Max.
Soil organic matter, 0-8"	%	2.0	0.7	1.0	2.9	2.7	0.8	0.7	3.4
Pre-plant soil nitrate-N, 0-48"	lb/acre	73	25	45	117	57	26	17	119
Estimated irrigation N input	lb/acre	16	9	2	30	28	20	8	80
Yield without N application (Y0)	bu/acre	151	35	90	220	166	28	105	212
Simulated yield potential (Yp)	bu/acre	276	26	230	327	260	24	217	304
Measured maximum yield	bu/acre	242	24	193	275	230	26	182	269
	% of Yp	88	7	81	100	88	7	82	100
At maximum return to fertilizer N (corn : N price ratio = 10:1):									
Optimal N rate (N)	lb/acre	168	58	90	265	120	27	69	158
Yield (Y)	bu/acre	236	25	189	267	227	26	180	262
% of observed max. yield	%	98	1	96	99	99	1	96	99
Yield increase from N ($\Delta Y = Y - Y0$)	bu/acre	84	37	15	129	61	25	23	90
Agronomic N use efficiency ($\Delta Y/N$)	bu/lb N	0.53	0.29	0.16	1.26	0.52	0.20	0.20	0.87
Partial factor productivity of N (Y/N)	bu/lb N	1.57	0.58	1.00	2.61	1.98	0.50	1.20	3.19
Residual soil NO_3-N	lb/acre	46	15	28	70	51	14	25	72

Yp - yield potential without any limitations by water, nutrients, or pests (Hybrid-Maize model, Yang et al., 2006)
Optimal N rate = N rate for maximum return at corn : N price ratio of 10:1, e.g., \$2.50/bu corn and \$0.25/lb N (EONR)
Agronomic efficiency = bu yield increase per lb of fertilizer-N applied
Partial factor productivity = bu yield per lb of fertilizer-N applied
Residual NO_3-N after harvest, measured in 0-4 ft depth (2003 and 2004, CC: N=7, CS N=11)

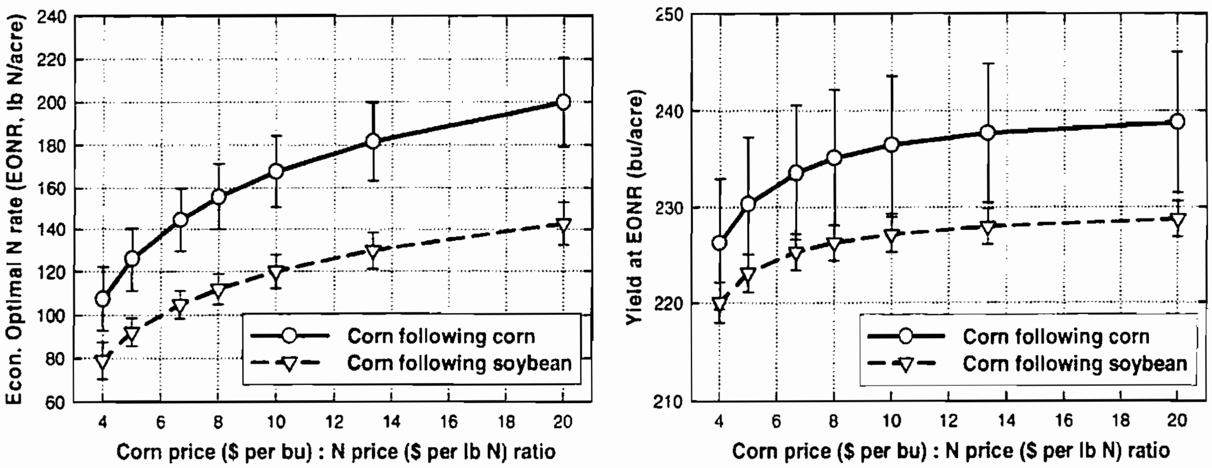

Figure 1. Influence of the corn : N price ratio on the economically optimal N rate (EONR) and irrigated corn yield obtained at the EONR. Values shown are averages and standard errors (bars) of 12 (CC) or 16 (CS) site-years in Nebraska, 2002-2004.

As expected, the EONR generally declined with a decrease in the corn : N price ratio, particularly below ratios of about 8:1. Along with this the difference in EONR between CC and CS became smaller too (Fig. 1). Yield response to N application varied more widely in corn following corn than in corn following soybean. Both the yield increase from applying N (ΔY) and the EONR varied less among site-years in CS than in CC (Table 1, Fig. 1). The standard deviation of the EONR was only 27 lb N/acre for CS as compared to 58 lb N/acre for CC. ΔY ranged from 23 to 90 bu/acre in CS as compared to 15 to 120 bu/acre in CC. Yield at the EONR varied widely for CC, but nor for CS (Fig. 1, right).

As others have reported before, the correlation between EONR and yield was relatively weak (r=0.31). However, yield at EONR was positively correlated with yield potential (r=0.72), whereas EONR was positively correlated with ΔY (r=0.50). The ΔY, on the other hand, was negatively correlated with Y_0 (r=-0.68) but positively correlated with the agronomic N use efficiency (AE, r=0.78), which is defined as the increase in crop yield per lb N applied (AE = $\Delta Y/F$). Across all 28 site-years in this study (Table 1), EONR was explained by the following multiple regression model:

$$EONR = 99.5 + 2.1\, Y_{EONR} - 2.1\, Y_0 - 241.3\, AE, \qquad R^2 = 0.90, \text{ all coefficients } P<0.001$$

Although the average AE at the EONR was the same for both rotations (about 0.52 bu yield increase per lb additional N applied), it varied widely among site years, from about 0.20 to more than 1 bu/lb (Table 1). AE is the product of the recovery efficiency (RE, lb fertilizer N recovered in the crop per lb N applied) and the physiological efficiency (PE, bu grain yield increase per lb additional N uptake in the crop resulting from fertilizer) of added N:

$$AE = RE \times PE$$

$$RE = (U - U_0)/F \qquad \text{and} \qquad PE = (Y - Y_0)/(U - Y_0)$$

where U is the total crop N uptake with application of fertilizer, U_0 is the crop N uptake without fertilizer addition (from indigenous N sources), and F is the amount of N applied. Y_0 or U_0 represent the amount of N recovered by the crop from all available indigenous N sources, including residual soil inorganic N, N mineralized from organic matter (soil organic matter, crop residues, manure), and N supplied by irrigation and atmospheric deposition. Thus, directly or indirectly Yp, Y_0 and AE have impact on the EONR and all three are affected by climate, soil, and management choices. Yp can be increased by optimizing planting date, hybrid, and plant population with regard to the climatic conditions of a site (Yang et al., 2006). Y_0 depends on the inherent soil conditions and soil and crop management factors such as tillage, crop rotation and residue management. AE will decline with (i) increasing N supply from indigenous sources, (ii) increasing fertilizer rate, (iii) poor N management causing high losses or (iv) any other limitations on the crop N sink, which may include drought stress, imbalanced nutrition, or pests (Cassman et al., 2002). The interactions of environmental and management factors with Yp, Y_0, and AE cause the spatial and temporal variation in EONR that is often observed.

Nitrogen Recommendations in the Corn Belt

Nitrogen recommendations for corn in the Midwest can be divided into (i) algorithms that include a yield goal and various estimates of soil N supply (Shapiro et al., 2003; Leikam et al., 2003) and (ii) recommendations that do not include yield goals and mostly focus on optimal N rates derived from yield response curves (Vanotti and Bundy, 1994; Sawyer and Nafziger, 2005). Both usually also account for other factors such as different previous crops or manure.

Yield goal-based approaches vary among states in terms of specific coefficients used (e.g., calculation of crop N requirement from yield goal) and how inorganic soil N and/or soil N supply from organic matter are accounted for (Fig. 2). Such fertilizer algorithms are primarily used in Western Corn Belt/Great Plains states such as Colorado, Nebraska, Kansas, South Dakota, and Missouri (Fig. 2). Typical for these environments is that both irrigated and dryland corn is grown so that the yield variation among counties is large (Fig. 3), significant continuous corn areas occur, soil organic matter, soil nitrate, and nitrate input from irrigation vary widely (see Table 1 for the Nebraska case study). In such environments, using a flat N rate would probably make little sense. The major theoretical advantage of detailed N algorithms is that they allow for more fine-tuning of N recommendations to site-specific needs, which also makes them suitable for variable rate N application (Koch et al., 2004). They also have substantial educational value by separating the major components of the N cycle in a more explicit manner. However, yield goals must be set properly by taking into account the climatic yield potential <u>and</u> the site yield history or soil yield potential (Dobermann and Shapiro, 2004). Likewise, accurate soil sampling and analysis for assessing the various components of soil N supply is required. Economics can be incorporated into such approaches through changing yield goals according to price changes or through additional empirical factors (Dobermann et al., 2006).

Flat, regionalized N rates that represent the average EONR for maximizing the return to N and some range (± $1/acre) around it have recently been proposed for states such as Iowa, Minnesota, Illinois and Wisconsin (Sawyer and Nafziger, 2005). They are purely based on statistical analysis of numerous N response functions compiled in large databases. The resulting recommendation is a blanket N rate for a whole state or sub-region within a state to account for major variation in N response (Fig. 2). This approach greatly simplifies the decision-making process because it eliminates the need for specifying a yield goal, assessing soil N status, or making assumptions about N use efficiency. However, it offers little potential for site-specific adjustments and also seems to be counter-intuitive to precision farming concepts such as variable rate N application by management zones, which has been shown to be profitable (Koch et al., 2004).

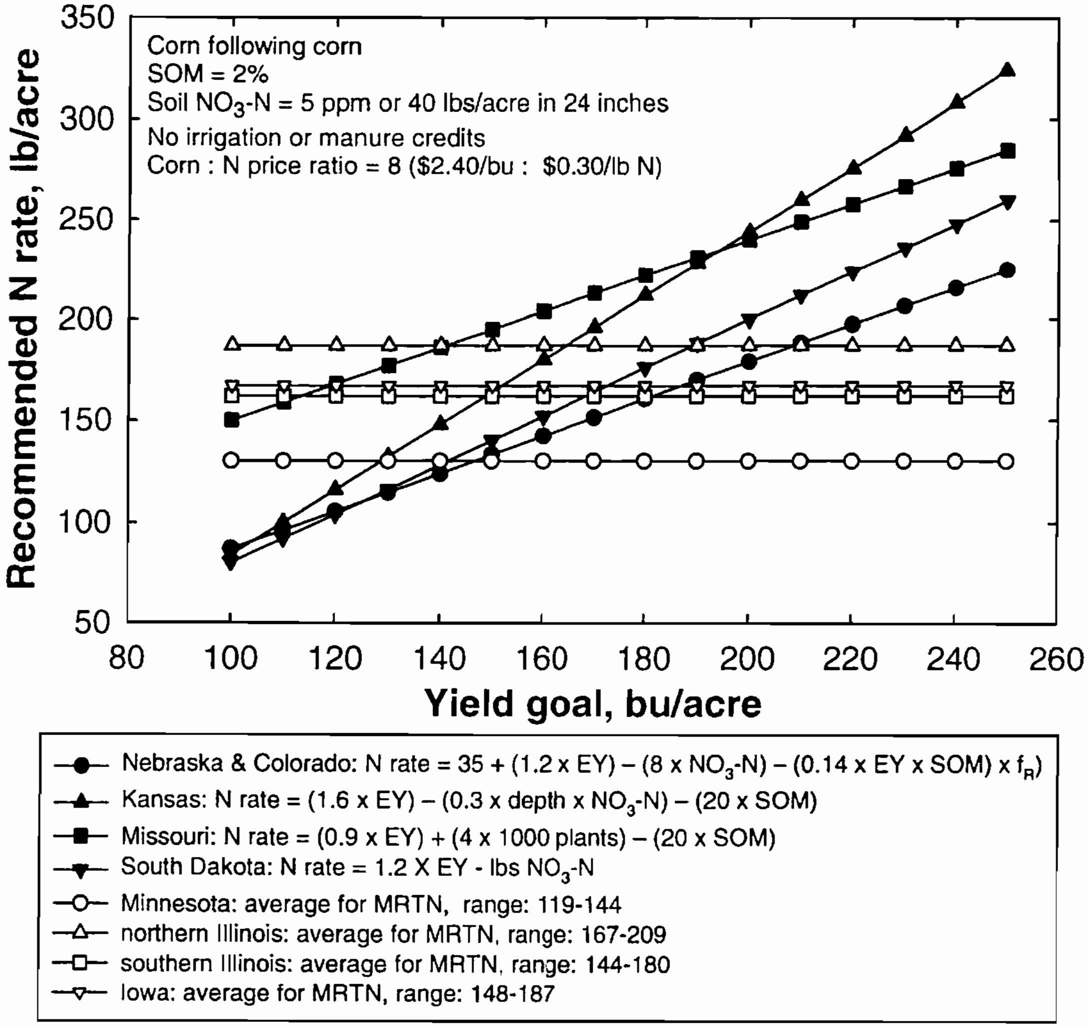

Figure 2. Nitrogen recommendations for corn following corn in selected states of the Midwest.

Although little input information is required to make the recommendation (prices of corn and N, previous crop), the resulting N recommendation hinges on the assumption that the (true) site-specific EONR is close to the average EONR for the price scenario specified. Because net return often changes little with varying the N rate around the EONR, a relatively wide N rate range is given in these regionalized blanket recommendations, usually about ±20 lb/acre around the suggested average N rate (Fig. 2, legend). The suggested N rate also depends on whether non-responsive sites are included in the data analysis or not. Potentially problematic is also that many of the initially assembled datasets (Sawyer and Nafziger, 2005) include older N response trials and long-term experiments, which may not represent current conditions. No-till sites were underrepresented (12%) and older data do not account for improvements in corn hybrids, particularly increasing tolerance to biotic and abiotic stresses (Duvick, 2005). In long-term experiments, soil N depletion occurs over time in plots with low or no N application. This affects the shapes of N response curves and may bias the calculated EONR to a degree that is not common in farmers' fields, where N is always applied. Sawyer and Nafziger (1995) concluded that the MRTN approach will require aggressive research programs for updating N guidelines and making them more specific to geographic locations, soils, rotations or other situations.

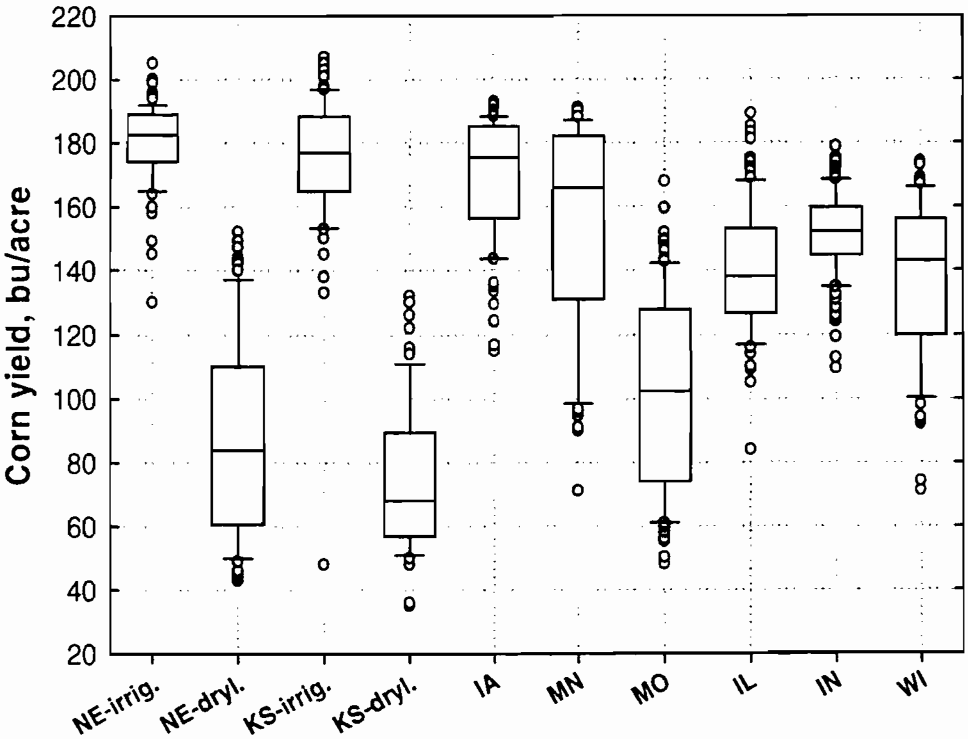

Figure 3. Corn yield ranges in selected states. Boxplots for each state represent county yields in 2005 (horizontal line = median, box = 25 to 75% percentiles).

Two major reasons were given as justification for this approach (Sawyer and Nafziger, 2005): (1) the apparent lack of correlation between the EONR and yield level at the EONR and (2) the perception that fertilizer-N algorithms that are based on soil tests and/or yield goal may lead to overprediction of N rates in years with poor response to fertilizer due to unfavorable climate or inaccurate soil NO_3 testing (Bundy et al., 1999). We have already discussed above that a poor correlation between EONR and yield does not imply that a yield goal is worthless. With regard to (2), there is no guarantee that a flat N rate approach would, on average perform better than a more complex fertilizer algorithm. We will examine this issue below. There are, however, geographical differences that may cause a narrower range of EONR in the central and eastern parts of the Corn Belt: compared to the Great Plains/Western Corn Belt states, yield variation tends to be smaller in states such as Iowa, Illinois or Indiana (Fig. 3), there is less variation in soil organic matter, more off-season precipitation makes pre-plant soil testing for nitrate less useful, corn-soybean is the predominant crop rotation, and there is little irrigation.

Figure 2 illustrates the different approaches in an example. Depending on where it is grown and what recommendation approach is used, the recommended N rate for a corn crop following corn and a yield of 200 bu/acre may vary anywhere from about 130 to 250 lb N/acre. Among N algorithms that include yield goal and soil testing, recommended N rates in Kansas and Missouri are generally much higher than those in Nebraska or South Dakota, but it remains unclear whether such high N rates are really justified. Where a flat N rate approach is used, the recommended N rate varies by 60 lb N/acre among states (127 to 187 lb/acre). Irrespective of this, however, the recommended N rate for a 100 or 150 bu corn crop is the same as that for a 250 bu crop. Whether such a wide range of yields can be achieved with the same N rate and at high levels of N use efficiency remains questionable.

A Comparison of Different Nitrogen Recommendation Approaches

We used the N response trials conducted in Nebraska during 2002 to 2004 (Table 1) to compare three different N recommendation approaches:

1. UNL - original University of Nebraska N algorithm for corn (Shapiro et al., 2003):
2. UNLm - modified University of Nebraska N algorithm for corn (Dobermann et al., 2006)
3. MRTN - flat, regionalized N rate approach, i.e., using the average EONR for CC and CS to achieve maximum net return (Sawyer and Nafziger, 2005).

The University of Nebraska's algorithm for estimating N fertilizer recommendations in corn predicts the N rate as a function of crop N required for achieving a certain yield goal (expected yield), soil organic matter (SOM), nitrate content in the soil profile, and other N credits such as previous crop, manure and irrigation:

N-rate (lb/acre) = 35 + (1.2 EY) – (0.14 EY x SOM) – (8 NO_3-N)– other N credits

EY = expected yield (bu/acre), e.g., 5-year average yield + 5%

NO_3-N = root zone soil residual nitrate-N in 2-4 ft depth, depth-weighted average (ppm)

SOM = soil organic matter content in 0-8" depth (%)

This algorithm was recently further modified to adjust N rates according to different time of N application and maximizing profit at different corn : N price ratios (Dobermann et al., 2006):

N-rate (lb/acre) = [35 + (1.2 EY) – (0.14 EY x SOM) – (8 NO_3-N)– other N credits] × f_A × f_R

f_A = application timing adjustment factor (0.95, 1.0, or 1.05)

f_R = corn : nitrogen price ratio adjustment factor

In our example, f_A was set to 1.0, which represents a standard pre-plant + sidedress N management strategy. The price adjustment factor increases or decreases the recommended N rate relative to a baseline corn to N price ratio of 8:1 (f_R = 1.0), i.e., f_R is >1 for price ratios greater than 8 and <1 for ratios less than 8, when N is expensive relative to corn.

In approach (3), the EONR was calculated for each site-year by fitting two different N response functions to the measured corn yields and obtaining the N rate at which net return was maximized (MRTN) for a range of different corn to N price ratios (from 4:1 to 20:10). For each price ratio and site-year, the average EONR was obtained. Average EONR for different price scenarios were then obtained for CC and CS, respectively. The fitted site-year specific EONR were used as the benchmark for evaluating the performance of the three N recommendation approaches. For each approach, recommended N rates were plugged into the two yield response functions fitted for each site-year data set and yields and net returns were calculated. In the two UNL N approaches, input data for calculating site-specific N rates included (1) yield goal based on past yields and known site yield potential (Dobermann and Shapiro, 2004), (2) measured soil organic matter content (average of 40 samples, 0-8" deep), (3) measured residual soil nitrate in Spring (average of 20 soil cores, 0-4 ft deep), and (4) N credits for previous crop and N input from irrigation water. In the UNLm approach, corn : N price ratio was another input variable. In the MRTN approach (3), the N rate only varied by corn : N price ratios and crop rotation, but was the same among site-years in CC and CS, respectively (= flat N rates).

The original UNL N algorithm performed well in terms of approaching the recommended N rate, yield and profit obtained for the EONR at price ratios of 10:1 to 8:1 (Fig. 4.). However, it exceeded the EONR by more than 10 lb/acre at price ratios of less than 8:1 (expensive N) or more than 12:1 (cheap N and/or expensive corn), which would result in average profit losses of more than $4/acre in those situations. In the UNLm approach, the simple empirical adjustment made by adding the price ratio factor (f_R) resulted in average N rates that were within 0 to 5 lb N/acre of the EONR across all price scenarios (Fig. 4, top left) and consistently improved profitability as compared to the original UNL algorithm (Fig. 4, bottom left). As designed, the flat N rate (MRTN) approach matched the average EONR perfectly (Fig. 4, top left), but it resulted in consistently lower net returns than those obtained with the two site-specific approaches using the original and the modified UNL equations (Fig. 4, bottom left). For price ratios of 6-10:1. net profit with the MRTN approach was on average about $2-3/acre less compared to that obtained with the modified UNL equation.

The UNLm approach also had the lowest standard error of the net return difference to the site-specific EONR in all price scenarios evaluated (Fig. 4, bottom right). The standard error of the difference between the net return obtained with a prescribed N rate and the net return at the EONR is an indication of how reliable a fertilizer recommendation algorithm is across sites. A smaller standard error indicates a more robust approach across a wider range of conditions.

More detailed analysis revealed that the poorer performance of the MRTN approach was primarily the case for corn following corn (Fig. 5, bottom left). In CC, the MRTN approach was, on average, about $4-6/acre less profitable than the UNLm algorithm for price ratios of 6-10:1. However, No significant profit difference was observed for corn following soybean. This seems to confirm the greater variability of N demand, N supply and N efficiency components in CC systems compared to CS, resulting in a generally wider range of EONR (Table 1, Fig. 1).

We also assessed the impact of utilizing the UNLm approach or the MRTN approach on residual soil NO_3-N after harvest. For two years, 2003 and 2004, residual NO_3-N was measured at all sites and in all five N rate treatments in 0-4 ft depth. Soil nitrate was plotted against N rate and a site-specific soil nitrate response function was fitted to each data set. This function was then used to estimate the residual nitrate levels for each site-year for the EONR as well as for the N rates prescribed with the different recommendation approaches. Interestingly, in both CC and CS, residual nitrate levels with the UNLm approach were closer to those obtained with the site-specific EONR (closer to a difference of 0) than by using a flat N rate obtained with the MRTN approach (Fig. 5, bottom right). However, the estimated differences in residual soil nitrate-N were generally small and need further validation.

The data set used in this exercise came from a relatively narrow range: high-yielding irrigated corn in Nebraska. Most likely, differences in the performance of different N recommendation approaches will be even greater when a wider range of environmental and management conditions is included. Such studies need to be conducted in the future. Nevertheless, our results illustrate no significant advantage of a flat N rate approach other than being simple. One could argue that at least for corn following soybean the EONR appears to be relatively stable across sites and perhaps also from year to year, probably because soybean is very efficient in extracting inorganic N from the soil profile and because it adds relatively consistent amounts of mineralizable crop residue N. However, to cover the whole range of crop rotations and environmental conditions requires a quantitative N recommendation algorithm that accounts for crop N demand, N supply, N efficiency and prices. In any case, using a yield goal approach always requires that N supply from indigenous sources is also accounted for because otherwise it would lead to gross overestimation of N rates. This has been the fundamental problem with older approaches such as the N rate = 1.2 × yield goal paradigm.

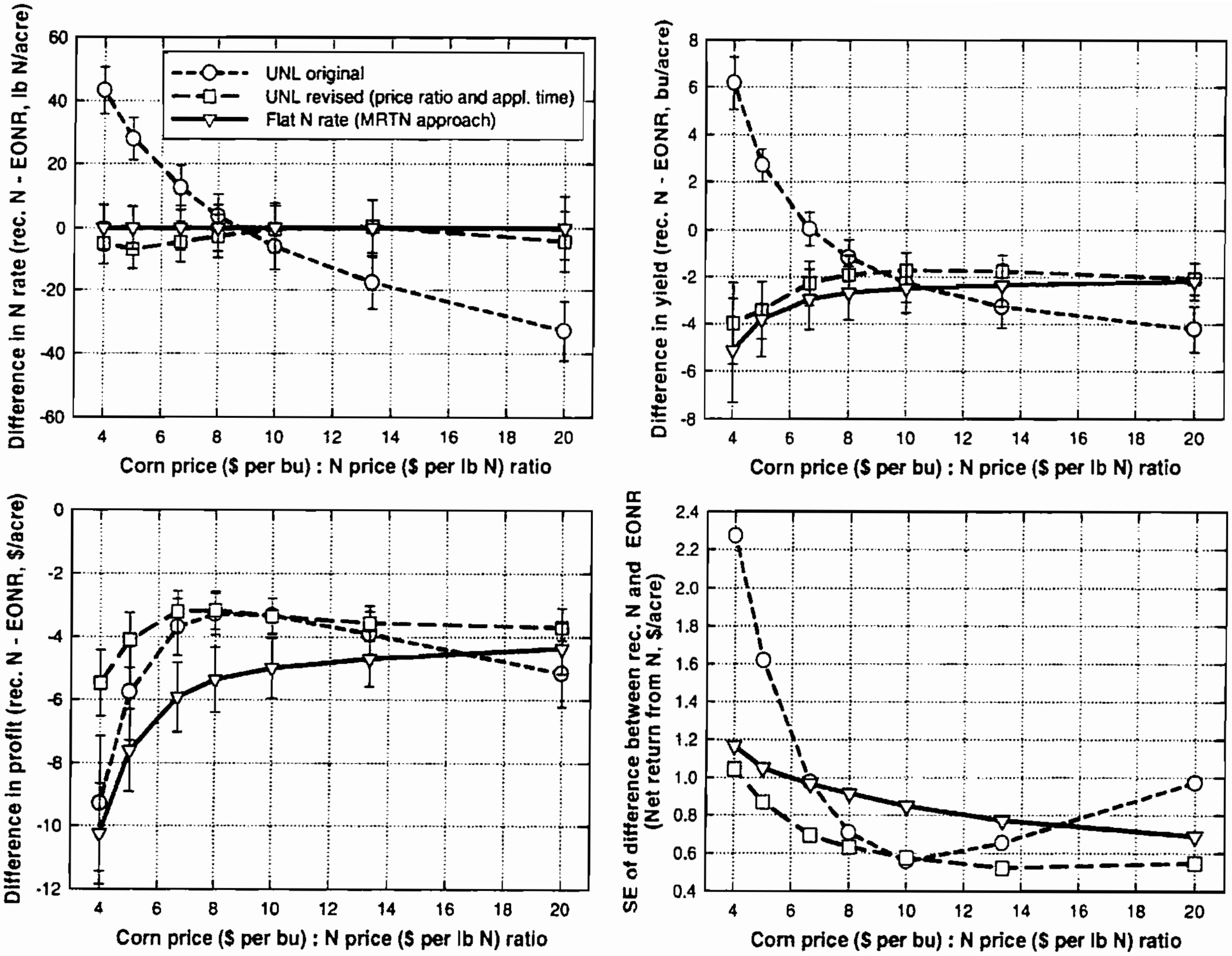

Figure 4. Comparison of three N recommendation approaches in N response trials with irrigated corn in Nebraska, 2002-2004. Values shown are means and standard errors of 28 site-years, including continuous corn (12) and corn following soybean (16).

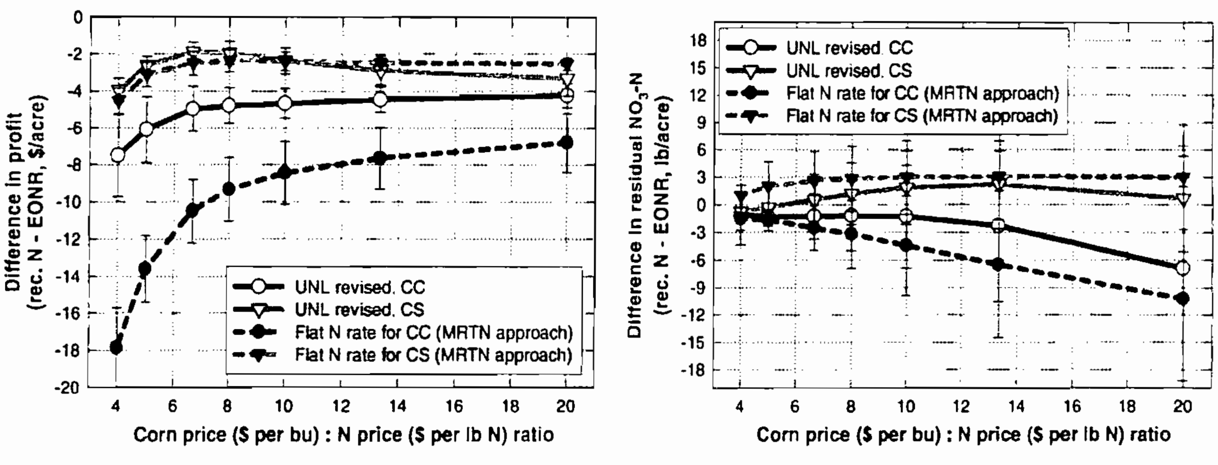

Figure 5. Comparison of the modified University of Nebraska N recommendation with the flat N rate approach in N response trials with irrigated corn in Nebraska, 2002-2004. Values shown are means and standard errors of continuous corn (12 site-years) and corn following soybean (16).

The weakness of the current yield goal and soil test-based N algorithms is that they do not explicitly include N use efficiency and that prices are handled in an empirical manner. This makes it difficult to account for different N use efficiencies associated with different N application methods. A general equation for calculating the fertilizer requirement (F) of a crop is:

$$F = (Y - Y_0)/AE = \Delta Y/AE \quad \text{or, transformed into nitrogen terms,} \quad F = (U - U_0)/RE$$

The latter is the same as Stanford's mass balance expression, $N_f = (N_y - N_s)/E_f$ (see P. Fixen, this proceedings). Yield (Y) or N uptake (U) can be chosen to maximize net return in relation to the attainable site yield potential and prices. We do have opportunities to improve existing N algorithms so that they better represent all three components of crop response to N addition:

1. **Y** or **U**: We have a better quantitative understanding of corn yield potential, how to set adequate yield goals for specific combinations of environment and corn management (Dobermann and Shapiro, 2004), and how to model crop N requirements in relation to yield (Dobermann and Cassman, 2002).
2. $\mathbf{Y_0}$ or $\mathbf{\Delta Y}$: We can use technologies such as variable rate N applicators and yield monitors to measure Y_0 and/or ΔY in the field by establishing small N omission or N rate strips/plots on-the-go. Alternatively, soil tests and other information on N supply from indigenous sources can be calibrated towards estimating Y_0 (or U_0).
3. **AE** or **RE**: In well-managed systems with favorable water supply, target AE should be about 0.5 bu/lb N and crop N recovery should be about 60%. Those values could be varied to account for N application timing and methods as well as other site-specific factors that could cause lower or higher N use efficiencies.

This approach is already being used elsewhere, for example in site-specific nutrient management of corn and rice in Asia (Dobermann et al., 2004; Witt et al., 2006).

Conclusions

Flat N rate recommendations that are based on a statistical summary of yield response curves do not have theoretical advantages over more detailed fertilizer algorithms that account for the major components of N demand, N supply, and N efficiency. Blanket recommendations will only work in environments with relatively less variation in cropping practices, soils and yield potential, i.e., where variation in EONR tends to be small too. Quantitative N recommendation algorithms that account for crop N demand, N supply, N efficiency and prices enable site-specific adjustment of N rates to wider ranges of environmental and management conditions and they possess a high educational value as well. However, improvements in these algorithms are possible. Using a yield goal only makes sense if the fertilizer algorithm includes the major components of crop N demand and N supply from soil and other indigenous sources.

Modern, tactical N management concepts should involve a combination of anticipatory (before planting) and responsive (during the growing season) decisions. The N recommendation approaches assessed here are suitable for making general decisions on the average amount of N needed and also for adjusting pre-plant or early N applications according to major variations in soil N supply. Combining this with in-season assessment of crop N and biomass status at few, key growth stages of corn is likely to provide another level of fine-tuning because it allows optimizing N use efficiency with regard to the seasonal yield potential.

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