Nitrogen Use Efficiency of Irrigated Corn for Three Cropping Systems in Nebraska

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ABSTRACT

Nitrogen use efficiency (NUE) is of economic and environmental importance. Components of NUE were evaluated at in 32 irrigated corn (*Zea mays* L.) trials conducted across Nebraska with different N rates and where the previous crop was either corn (CC), drybean (*Phaseolus vulgaris* L.) (CD), or soybean [*Glycine max* (L.) Merr.] (CS). The mean grain yield with adequate nutrient availability was 14.7 Mg ha^{-1}. When no N was applied, measured soil properties and irrigation water N accounted for <20% of the variation in plant nitrogen uptake (UN). Mean fertilizer N recovery in aboveground biomass was 74% at the lowest N rate compared with 40% at the highest N rate, a mean of 64% at the economically optimal nitrogen rate (EONR), and least with CD. Agronomic efficiency of fertilizer N averaged 29 kg grain kg^{-1} N at EONR and was also least with CD. Partial factor productivity of N averaged 100 kg grain kg^{-1} N at EONR, and was greater with CS compared with CC and CD. After harvest, residual soil nitrate nitrogen (RSN) in the 0- to 1.2-m depth ranged from 21 to 121 kg ha^{-1} and increased with N rate. Mean RSN was 88, 59, and 59 kg ha^{-1} for CD, CC, and CS, respectively. High corn yields can be achieved with high NUE and low RSN by management to maximize profitability in consideration of yield potential, and by applying N at the right amount and time.

Nitrogen fertilizer will continue to be indispensible for meeting global food, feed, and fiber needs. Voroney and Derry (2008) estimated that 340 million Mg yr^{-1} N is fixed by natural means, including lightning and biological N fixation, and 105 million Mg yr^{-1} is fixed by human activities, including burning of fossil fuels and N fertilizer production, with N fixation by human activities expected to continue to increase. Townsend and Howarth (2010) estimated the amount of N fixed by human activities to be about 180 million Mg yr^{-1}, with most used as mineral fertilizer. Fertilizer N production has important environmental implications with an average of ~2.55 kg CO_2 emitted per kg fertilizer N fixed and transported (Liska et al., 2009). The amount of N applied is associated with emission of N_2O (IPCC–OECD, 1997) and N accumulation in sensitive aquatic, marine, and terrestrial ecosystems (Groffman, 2008; Malakoff, 1998). The challenge is to produce more grain to meet growing global needs with high NUE.

Nitrogen use efficiency, or grain production per unit of available N in the soil, is composed of the efficiency of N uptake and of conversion of total UN to grain (Moll et al., 1982). Corn NUE has an impact on energy efficiency, profitability, water protection, and CO_2 and N_2O emission. High N requirement for high yield cereal systems can lead to substantial N losses to the environment and low NUE with suboptimal management and yields well below the attainable yield potential (Cassman et al., 2002). Globally, 46% of the N input for crop production is from inorganic fertilizers with biological N fixation, atmospheric deposition, animal manure, and crop residues being major sources (Smil, 1999). The main factor affecting NUE is N application rate with excess N supply causing reduced NUE (Meisinger et al., 2008). Efficient N recovery with minimal losses of N to denitrification, leaching, and volatilization is important to NUE which in turn will improve natural resource protection and profitability (Raun and Schepers, 2008). The potential for N loss increases as inorganic N, and especially NO_3–N in the soil profile increases (Cassman et al., 2002). Crop NUE is a function of efficiency of recovery of indigenous soil nitrogen and applied nitrogen (RE), and internal efficiency of nitrogen use within the plant (IE), specifically conversion of UN to grain.

Uptake of indigenous soil N by the crop is important to NUE and includes uptake of N from RSN, net mineralization of N from soil organic matter (SOM) and crop residues, atmospheric N_2 fixation, wet and dry deposition of atmospheric NH_4, and NO_3–N in irrigation water. Considering RSN in formulating N recommendations for corn is common in subhumid corn production areas where risk of leaching and denitrification loss

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Published in Agron. J. 103:76–84 (2011)
Published online 3 Nov 2010
doi:10.2134/agronj2010.0189

Abbreviations: AE, agronomic efficiency of nitrogen use; BE, biomass efficiency of nitrogen use; CC, CD, CS, corn following corn, dry bean, and soybean, respectively; EONR, economically optimal nitrogen rate; IE, internal efficiency in converting total plant accumulated nitrogen, taken up both from the indigenous soil and fertilizer nitrogen, into grain yield; NHI, nitrogen harvest index; NUE, nitrogen use efficiency; N_0, no nitrogen applied; PE, physiological efficiency of fertilizer nitrogen use; PFP, partial factor productivity; RE, recovery efficiency of applied nitrogen in aboveground biomass; RSN, residual soil nitrate nitrogen; SOM, soil organic matter; UN, total nitrogen in the aboveground biomass at physiological maturity.

is relatively low, but may be applicable in many humid, higher risk areas as well (Meisinger et al., 2008). Estimates of N availability from mineralization of SOM-N are often considered in N recommendations but there is much annual variation in the amount of N mineralized (Griffin, 2008). The University of Nebraska–Lincoln algorithm for estimating N fertilizer recommendations for corn predicts the amount of N needed as a function of crop N required for a yield goal, SOM, RSN in a soil depth of 0.6 to 1.2 m, and other N credits such as previous crop, manure, and NO_3–N applied in irrigation water (Shapiro et al., 2009). The coefficients in the algorithm were derived from regression analysis of 81 site-years of N rate experiments conducted on irrigated and rainfed land during 1976 to 1982, with further validation done during 2001 to 2004 (Dobermann et al., 2011). However, accurate prediction of indigenous soil N supply remains a major challenge (Oberle and Keeney, 1990; Cassman et al., 2002; Laboski et al., 2008).

An important component of NUE is nitrogen recovery efficiency (RE). It affects profitability and RSN remaining after harvest, with RSN subject to leaching and denitrification losses (Cassman et al., 2002). As N rate increases, RE is expected to decrease and RSN to increase. This was illustrated by Lord and Mitchell (1998) who estimated a RE of 0.52 to be an inflection point for wheat (*Triticum aestivum* L.) on sandy soil below which there was a substantially increased rate of RSN accumulation.

Grain yield per unit of UN, or internal efficiency (IE), is determined by nitrogen harvest index (NHI), or the efficiency of UN allocation to grain (NHI), and by grain N concentration (Moll et al., 1982). A component of IE is physiological efficiency of fertilizer use (PE), the change in grain yield relative to the change in UN due to application of N. Crop partial factor productivity (PFP) is total grain yield relative to amount of N applied. Agronomic efficiency (AE), the increase in grain yield per unit N applied, is the product of RE and PE (Cassman et al., 2002). The efficiency values vary due to effects and interactions of management, genetics, and environment.

Crop rotation, tillage, and N management can be important to N use efficiency and minimizing losses (Raun and Schepers, 2008). The NUE of soybean–corn rotations is commonly higher than for continuous corn (Raun and Schepers, 2008). In a lysmeter study, however, Klocke et al. (1999) found a higher leachate NO_3–N concentration for the rotation with 91 and 52 kg ha^{-1} yr^{-1} lost to leaching for CS and CC, respectively. Denitrification is often greater with no-till compared with tillage with 25 and 11 kg ha^{-1} yr^{-1} lost in South Dakota for no-till and plow tillage, respectively (Hilton and Fixen, 1994). Rice and Smith (1982) also observed more denitrification with no-till compared with plowed soil and attributed the greater loss to a higher soil water content with no-till. Parkin and Kaspar (2006), however, did not observe significant effects of tillage on N_2O emissions. Immobilization of N is affected by the amount and C/N of the crop residue, but also by tillage with generally greater immobilization with no-till compared to tillage (Doran, 1980). Nitrogen requirement with no-till may be greater until a N dynamics equilibrium is established for the soil–plant system (Raun and Schepers, 2008). The results of several studies reporting increased NUE with split application compared with all N applied preplant were reviewed by Raun and Schepers (2008).

Yield in excess of 15 Mg ha^{-1} is increasingly common for irrigated corn in Nebraska. Corn following corn or CS is most common in the state, but CD is important in western Nebraska. Better understanding indigenous soil N supply and the various components of NUE with high yield corn is important for efficient future corn production. The objectives of this research were to relate soil test results to N uptake and to quantify and better understand NUE for high yield irrigated corn under three cropping systems at differing N rates.

MATERIALS AND METHODS

Site Characteristics and Experimental Design

Nitrogen response trials were conducted at 11 or 12 locations per year representing the main corn production areas of Nebraska from 2002 to 2004 for 12, 4, and 16 site-years for CC, CD, and CS, respectively. The CC site-years were primarily in south central and west central Nebraska and included seven ridge-till and five disk-till site-years with seven silt loam, three loamy sand, and two sandy loam soils. The CD site-years were in western Nebraska with relatively high elevation and less precipitation and all were chisel plow and/or disk tilled with two sandy loam and two silt loam soils. The CS site-years were in eastern Nebraska and included 12 no-till and four disk-till site-years with eight silt loam, six silty clay loam, and two sandy loam soils. Additional details of site characteristics and crop management are reported in Wortmann et al. (2009) and Dobermann et al. (2011). All soils had rooting depths >1.2 m and the ranges of soil properties were 7 to 34 g kg^{-1} SOM and 30 to 254 kg ha^{-1} RSN in the 0- to 1.2-m depth before planting. Nitrate-N applied in irrigation water ranged from 20 to 90 kg ha^{-1} (Dobermann et al., 2011).

The effects of five N rates were evaluated: 0, 112 or 140, 168 or 196, 224 or 252, and 336 kg ha^{-1} for CC and CD; and 0, 56 or 84, 112 or 140, 168 or 196, and 280 kg ha^{-1} for CS. The higher sets of N rates were applied in 2003 and 2004 realizing that the 2002 rates did not always fully capture the response curve. The N fertilizer was ammonium nitrate with 40 or 60% of N applied preplant for sandy and medium texture soils, respectively. The remainder was side-dress applied at the sixth leaf colar stage (V6; Ritchie et al., 1996) for medium and fine texture soils, and in two equal rates at V6 and V10 for sandy soils. Fertilizer P and K were applied at 20 and 40 kg ha^{-1}, respectively, as triple superphosphate and muriate of potash to all plots used for determining NUE components. These P and K rates were found to be adequate for optimal crop performance (Wortmann et al., 2009). The fertilizers were surface broadcast applied without incorporation. Treatments were assigned in a randomized complete block design with four replications.

Surface soil samples for the 0- to 20-cm depth consisting of 10 cores per plot of ~1.8-cm diam. were collected with hand probes before planting and fertilizer application to determine soil pH and SOM by loss on ignition. Soil samples consisting of five cores per plot of ~3-cm diam. were collected with hydraulic probes before planting, and again after harvest, in 30-cm increments to a depth of 1.2 m and analyzed for NO_3–N concentration by water extraction and cadmium reduction (NCR-13, 1998). The quantity of RSN was determined from NO_3 concentration and estimated bulk density. Bulk density was measured for the 0- to 20-cm depth from cores collected in the spring, before tillage and avoiding wheel tracks, using a 2.5-cm soil probe with a plastic tube liner. Based on experience with soils in Nebraska, bulk density for deeper depths was assumed to be 105% of the surface soil bulk density realizing that the depth effect on bulk density varies with soils, fields, and time.

A six-plant sample was collected from each plot at physiological maturity to determine N concentrations in grain and stover (stalks, leaves, and cobs), and harvest index. The plants were cut at ground level and the ears and stover separated and weighed. The stover was shredded and subsampled. Ears and subsamples of stover were oven-dried. Ears were shelled and dry wt. of grain, cobs, and stover were obtained. Subsamples of each were milled and, using a total C and N analyzer, analyzed for N concentration by the Dumas dry combustion procedure (Bremner, 1996). Grain yield was determined from harvest of 15 m^2 of plot area in the center two rows and grain water concentration was measured. Grain yield (0.155 g g^{-1} water concentration), harvest index, and cob, stover, and grain N concentrations were used in calculation of biomass yield, UN in grain and biomass, NHI, and other NUE values.

Data Analysis

Statistical analyses were conducted using Statistix 9 (Analytical Software, Tallahassee, FL) unless indicated otherwise. Analyses were conducted separately by each cropping system unless indicated differently. Regression equations were selected based on the R^2, provided that the regression coefficients were significant at $\alpha = 0.05$.

Polynomial functions were determined for UN as a function on N rate and grain yield, and for grain yield as a function of UN as a measure of NUE using N rate means for each site-year. Regression analysis was used to relate RSN, UN, RE, PFP, AE, and PE to N rate, again using N rate means for site-years within cropping systems; the analysis for CS was done with and without three site-years included that had >50 kg ha^{-1} NO_3–N applied in irrigation water with the expectation that this additional N input would affect the NUE relationships. Because of correlation in NO_3–N concentration between depths, the MIXED procedure of SAS 9.1 (SAS Institute, Cary NC) was used for regression analysis with an autoregressive covariance structure to determine N rate and soil depth effects on RSN concentration after harvest with blocks and site-year as random effects; this procedure estimated RSN at EONR.

The potential to estimate soil N supply was evaluated using regression analysis with SOM, RSN before planting, soil pH, and NO_3–N applied in irrigation as independent variables, and UN with no fertilizer N applied as the dependent variable. This analysis was conducted using plot values with no N applied except for NO_3–N applied in irrigation for which there was only a single value per site-year. For this analysis, CC and CD site-years were combined as R^2 values were not improved by separating these.

Values of NUE (Cassman et al., 2002) were determined using N rate means of site-years. Recovery efficiency was calculated as RE = $(UN_{+N} - UN_{N0})$/N rate, with UN and N rate expressed as kg ha^{-1}. A consideration with this estimate of RE and other efficiencies estimated using UN is that UN was N in the aboveground biomass at physiological maturity; it does not account for N in roots and N that was taken up by the crop and lost to postanthesis NH_3 volatilization (Francis et al.,1993). Postharvest RSN was the amount in the 0 to 1.2 m soil depth measured in 0.3 m increments. Physiological efficiency of applied N was calculated as PE = $(Y_{+N} - Y_{N0})/(UN_{+N} - UN_{N0})$. Crop IE, or also called internal efficiency of all N taken up from soil and fertilizer, was determined as grain yield divided by UN. Agronomic efficiency of fertilizer N was calculated as AE = $(Y_{+N} - Y_{N0})$ N $rate^{-1}$. Crop BE was similarly calculated with Y = biomass yield rather than grain yield. Crop PFP was calculated as PFP = grain yield N $rate^{-1}$. The units for PE, IE, AE, BE, and PFP were kg kg^{-1}.

Cropping system effects on efficiency variables at EONR were compared using the MIXED procedure of SAS with site-year means as random effects and replications in a completely randomized design. Standard errors of mean adjusted for the number of observations appropriate for each comparison. As site-year effects contributed to the standard errors with this analysis, the analysis increased the probability of failing to detect cropping system effects when the effects were real, but reduced the probability of falsely finding cropping system effects to be real.

Nonlinear asymptotic regression analyses, which gave better fits compared with polynomial analysis, were conducted to develop equations for PFP and AE as affected by N rate. The incremental AE and BE as affected by N rate (δYield δN^{-1}) or the increase in yield for each 1 kg ha^{-1} increase in N rate were calculated. Corn RE was linearly related to N rate and PE was linearly related to N uptake. The values for these NUE indicators were determined for the mean EONR of 171, 93, and 122 kg ha^{-1} for CC, CD, and CS, respectively, with a fertilizer N to corn price ratio of 7 [\$ kg^{-1} (\$ $kg^{-1})^{-1}$] (Dobermann et al., 2011). The fertilizer N/corn price ratio of 7 was used as it was the most commonly occurring ratio. Differences were considered significant at $\alpha = 0.05$, and all reported regression coefficients, correlation coefficients, and equations were significant at $\alpha = 0.05$.

RESULTS

Nitrogen Uptake and Soil Nitrogen Supply

Mean corn UN was 252 kg ha^{-1} with a SE of 11.1 and a range of 50 to 457 kg N ha^{-1}. The range of UN across N rates was similar for CC and CS but much narrower for CD (Fig. 1). Corn UN can be estimated for grain yield (Y) according to the following equations:

$$UN_{CC} = -10.77 + 15.08Y + 0.227Y^2,\ R^2 = 0.71 \quad [1]$$

$$UN_{CD} = -1588 + 250.5Y - 8.569Y^2,\ R^2 = 0.56 \quad [2]$$

$$UN_{CS} = -44.4 + 19.85Y + 0.100Y^2,\ R^2 = 0.67 \quad [3]$$

The relationships were nearly linear for CC and CS but strongly quadratic for CD.

Corn UN with N_0, an estimate of indigenous soil N supply, ranged from 50 to 300 kg ha^{-1} with a curvilinear relationship of grain yield with UN (Fig. 2). The upper line in this figure indicates the maximum IE or N dilution in the plant at N_0 and when low N availability is limiting crop yield. The lower line is the mean IE for these UN levels at N_0.

Soil test values accounted for only 4 to 21% of the variation in UN with no N applied. Soil RSN, before planting and N application (mg kg^{-1}), and SOM (g kg^{-1}), but not soil pH, were generally related to UN. The best-fit equations, with one

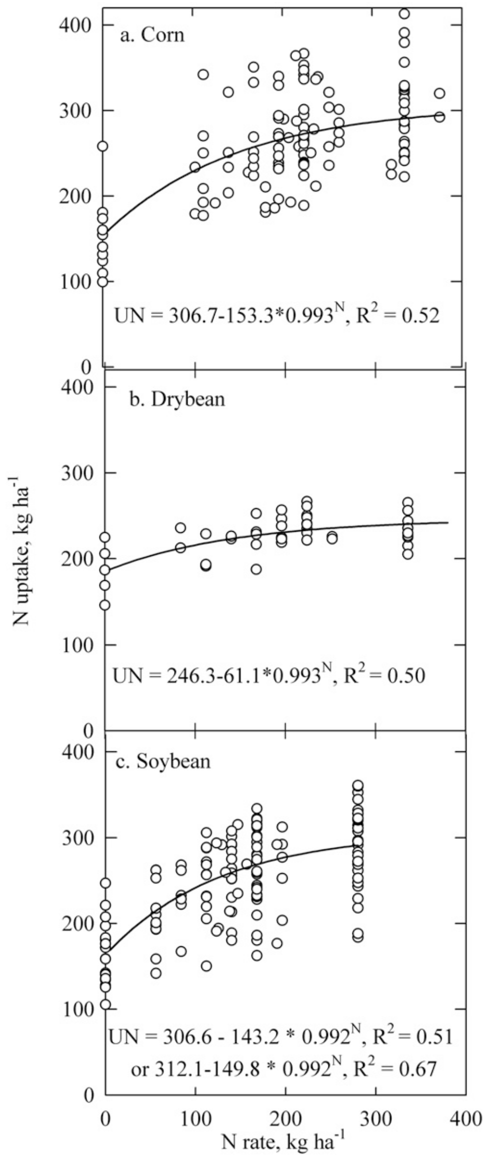

Fig. 1. Mean aboveground plant N uptake (UN) for 32 irrigated corn trials conducted in Nebraska for cropping systems where corn followed (a) corn, (b) drybean, and (c) soybean in rotation. The second soybean equation was estimated with three trials that had >50 kg NO_3–N applied in irrigation water excluded; the curve is for the first equation.

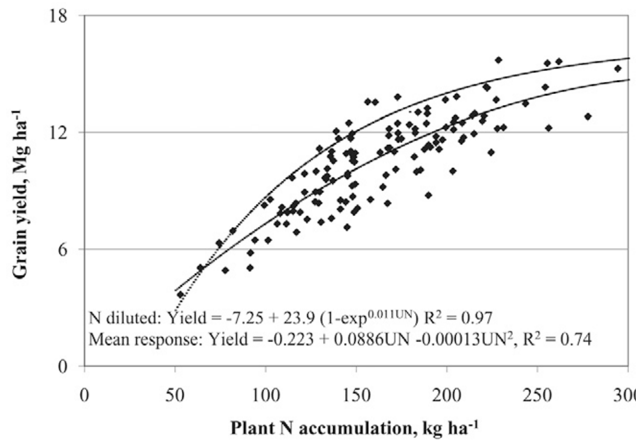

Fig. 2. Relationship of grain yield with plant N accumulation at physiological maturity for no N applied. The upper curve represents maximum dilution of N in the plant (maximum physiological efficiency) and the lower curve represents the mean efficiency in use of N supplied from the soil. The results are from 32 irrigated corn trials conducted in Nebraska.

CS site-year excluded because NO_3–N concentration in the irrigation water was 30 mg L^{-1} with approximately 90 kg ha^{-1} of NO_3–N applied (IrrN) were:

$$UN_{CC+CD} = 221 + 2.86\ RSN_{1.2m} - 3.10 \times SOM,\ R^2 = 0.12,\ n = 97 \quad [4]$$

$$UN_{CC+CD} = 172 + 3.96\ RSN_{1.2m} - 2.51 \times SOM + 1.91 * IrrN,\ R^2 = 0.19,\ n = 97 \quad [5]$$

$$UN_{CS} = 125.9 + 8.409\ RSN_{1.2m},\ R^2 = 0.19,\ n = 67 \quad [6]$$

$$UN_{CS} = 109 + 7.77\ RSN_{1.2m} + 0.711\ SOM,\ R^2 = 0.21,\ n = 67 \quad [7]$$

The R^2 values were increased for UN_{CC+CD} from 0.12 and 0.14 to 0.19 by including the amount of NO_3–N applied in irrigation water but this variable was not significant for UN_{CS}. Nitrate-N concentration in irrigation water, however, did not account for variation in UN_{CC+CD} or UN_{CS}.

With the exception of Eq. [6], the amount of UN accounted for by variation in RSN ranged from 12 to 254 kg N ha^{-1} and was <50% of the measured RSN. The results indicate nearly all recovered RSN was from the 0- to 90-cm depth with very little recovery from the 90- to 120-cm soil depth. Including SOM in the equation generally increased the R^2 values, but the SOM coefficient was negative for UN_{CC+CD}. The Y intercept was lower and the RSN slope higher for CS compared with CC+CD (Eq. [6], [7]), even though the range of RSN was narrowest for CS, implying less N supply from mineralization of organic N and more efficient use of RSN with CS compared with CC and CD. However, the low R^2 values indicate a need for caution in interpretation of suggested cropping system effects.

Nitrogen Use Efficiency

Mean RE was 70 to 85% at the lowest N rate with CC and CS compared with 40% at the highest N rate (Fig. 3). The effect of N rate on RE was linear and similar for the CC and CS site-years. For CD site-years, mean RE over all N rates was only 24% and less than with CC and CS (Table 1). At mean EONR, the RE was 67, 75, and 16% for CC, CS, and CD, respectively.

Change in RSN after harvest with N rates is a further indication of fertilizer N recovery. Postharvest RSN ranged from 21 to 121 with a median of 34 kg N ha^{-1} to a 1.2-m depth (Dobermann et al., 2011). More RSN remained after harvest for CD compared with CC and CS at EONR (Table 1). Concentration of RSN was correlated for adjacent depths with r = 0.56, 0.27, and 0.39 for CC, CD, and CS, respectively. There was increased postharvest RSN to the 1.2-m depth with increased N rate for all cropping systems, especially when N rate exceeded EONR (Table 2) and the mean amount of RSN was 117% more with the highest N rate compared with EONR (Fig. 4). Concentration of postharvest RSN was greater at the 0- to 30-cm depth than at greater depths at EONR but the depth effect was less consistent

Table 1. Indicators of N use efficiency as affected by cropping system at the economically optimal N rates (EONR)† for high yield irrigated corn in Nebraska following corn (CC), drybean (CD), and soybean (CS) in rotation.

Previous crop	Indicators of N use efficiency‡								
	UN	RSN	RE	IE	NHI	Grain N	PFP	AE	PE
	kg ha^{-1}		kg kg^{-1}						
Corn	262	59	0.67	57	0.65	13.3	83	29	44
Drybean	206	88	0.16	66	0.70	12.3	131	7	54
Soybean	250	59	0.75	57	0.64	13.1	117	30	40
	Comparison of cropping system effects								
CC-CD	*	0.09	***	*	ns§	ns	***	***	ns
CC-CS	ns	ns	ns	ns	ns	ns	***	ns	ns
CD-CS	ns	0.08	***	*	0.08	ns	**	***	ns

* Significant effect at $\alpha \le 0.05$.

*** Significant effect at $\alpha \le 0.001$.

† EONR = 171, 93, and 122 kg ha^{-1} for corn following corn, drybean, and soybean, respectively (Dobermann et al., 2011).

‡ UN, nitrogen uptake in aboveground biomass; RSN, residual soil nitrate nitrogen following harvest to 1.2 m depth; RE, nitrogen recovery efficiency; IE, efficiency of converting total plant nitrogen uptake to grain; NHI, nitrogen harvest index; PFP, partial factor productivity; AE, agronomic efficiency of fertilizer nitrogen use; and PE, physiological efficiency of fertilizer nitrogen use.

§ ns, no significant effect at $\alpha \le 0.05$.

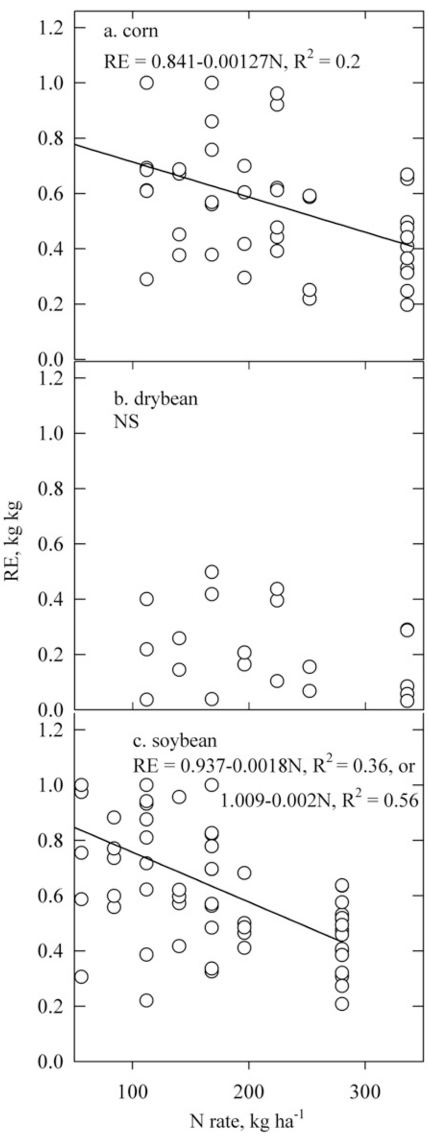

Fig. 3. Mean recovery efficiency of fertilizer N (RE), or aboveground plant N uptake per unit of fertilizer N applied, for 32 irrigated corn trials conducted in Nebraska where the previous crop was (a) corn, (b) drybean, and (c) soybean. The second soybean equation was with three trials that had >50 kg NO_3–N applied in irrigation water excluded; the curve is for the first equation.

at high N rates. The large increase in RSN for CD occurred with the 130 to 186 kg ha^{-1} N rate. Application of >200 kg ha^{-1} N to CD did not result in much additional increase in postharvest RSN indicating likely leaching losses.

Efficiency in converting total UN to grain yield (IE) is important to NUE and is determined by the efficiency of UN allocation to grain (NHI) and grain N concentration. The Pearson correlation coefficients of IE with NHI and grain N concentration were 0.49 and −0.65, respectively. Nitrogen rate did not affect NHI and mean NHI at EONR was 0.65 for CC and CS and 0.70 for CD (Table 1). The mean grain and plant N concentrations were 12.8 and 10.3 g kg^{-1}, respectively, with no effect of previous crop. There were 14 and 30% increases in grain and plant N concentration, respectively, at EONR compared with N_0 (Table 1, N_0 data not shown). The greater IE for CD, which had a low EONR compared with CC and CS, was because of higher NHI and lower grain N concentration (not significant) compared with CC and CS.

The mean UN over all cropping systems and N rates was 252 kg ha^{-1} at which IE was 58 kg kg^{-1} but IE decreased to 44 kg kg^{-1} at UN of 350 kg ha^{-1} (Fig. 5). At EONR, IE were 57, 57, and 66 kg kg^{-1} for CC, CS, and CD, respectively (Table 1). Grain yield was related to UN according to the following regression equations determined from plot data:

$$\text{Grain yield}_{CC} = -2.49 + 0.104\ \text{UN} - 0.000147\ \text{UN}^2,\quad R^2 = 0.80 \tag{9}$$

$$\text{Grain yield}_{CD} = 9.88 + 0.00687\ \text{UN} + 0.0000416\ \text{UN}^2,\quad R^2 = 0.41 \tag{10}$$

$$\text{Grain yield}_{CS} = 0.551 + 0.0817\ \text{UN} - 0.000111\ \text{UN}^2,\quad R^2 = 0.71 \tag{11}$$

$$\text{Grain yield}_{all} = -0.535 + 0.0903\ \text{UN} - 0.000126\ \text{UN}^2,\quad R^2 = 0.73 \tag{12}$$

Mean PFP for CC and CD decreased from approximately 125 to 40 kg grain yield kg^{-1} fertilizer N applied for the low and high N rates, respectively (Table 1; Fig. 6). The PFP was higher at the low N rate for CS compared with CC and CD but similar for all previous crops once N rate exceeded 150 kg ha^{-1}. The rate of change in PFP was inversely related to the rate of change in grain yield in response to rate of applied N. At the mean EONR, PFP was 83, 131, and 117 kg kg^{-1} for CC, CS, and CD, respectively, compared with a recent estimated mean for U.S. corn in 2000 of 57 kg kg^{-1} (Cassman et al., 2002).

Mean AE at EONR was highest for CC and CS, and lowest for CD (Table 1). Mean AE ranged from 40 to <20 kg of increased grain yield per kg N applied at the low compared with the high N rate for CC and CS (Fig. 7). For CD, AE was <20 kg for all N rates. The effect of N rate on AE was well demonstrated by the effect of applied N on incremental grain yield (Table 3). Mean incremental AE declined sharply for all cropping systems as N rate increased above EONR. Similarly, the incremental increase in biomass yield per unit of applied N decreased with N rate.

Mean PE of fertilizer N use at EONR was 43.2 kg grain kg^{-1} N and was similar for all cropping systems (Table 1). The relationship of PE with N rate was weak with decreased efficiency as N rate increased (Fig. 8). The relationship of PE with N rate was strengthened when three site-year with >50 kg ha^{-1} N applied in irrigation water were excluded from the analysis with R^2 increased from 0.11 to 0.27.

DISCUSSION

The results from this study clearly demonstrate the potential to produce high corn yields with recovery of most applied N during the season of application and with modest RSN after harvest. Use of irrigation to supplement rainfall greatly reduces the variability in growing conditions and yield, enhancing the potential to manage for high NUE. The components of NUE often showed more efficiency at EONR than at higher N rates. Therefore, application of N near to EONR is important to NUE. Split application, with much of the N applied in-season near to or at the time of high N uptake, likely contributed to high NUE as found by others (Wuest and Cassman, 1992; Raun and Schepers, 2008).

Indigenous soil N supply supported much UN and grain yield (Fig. 1 and 2). The upper line of Fig. 2 indicates the maximum IE or N dilution in the plant when low N availability is limiting crop yield. This response curve corresponds well to that determined by Cassman et al. (2002) using other corn yield results for the north-central United States. The lower line is the mean grain yield for these UN levels with N_0. Grain yield below the upper line indicates that low N availability is not the only limiting factor to grain yield. The curvilinear lines illustrate the reduced efficiency in the conversion of N to grain as UN increases. The frequent occurrence of high UN with N_0 indicates the importance of soil supplied N to grain yield, which needs to be adequately considered in estimating fertilizer N requirements. However, measured soil properties accounted for <20% of UN at N_0, demonstrating difficulty in predicting indigenous soil N supply as indicated by Eq. [5] to [8]. Scrutiny of the site-year means for UN at N_0 did not indicate that conventional tillage compared with ridge till or no-till and that sandy compared with medium texture soil affected UN. Soil organic matter concentration, however, accounted for significant variation in EONR for CS in this set of trials, and an algorithm considering SOM, RSN and other factors

Table 2. Effect of fertilizer N rate applied to irrigated corn on postharvest residual soil NO_3-N concentration.

N rate	Soil depth, m 0–0.3	0.3–0.6	0.6–0.9	0.9–1.2
kg ha^{-1}	mg kg^{-1}			
	Previous crop = corn; 12 site-years			
0	4.6cA†	2.1bB	1.7bB	1.5bB
EONR‡	6.9bA	2.5bB	2.3bB	2.3bB
336	10.3aA	6.7aB	5.8aB	5.4aB
	Previous crop = drybean; 4 site-years			
0	3.6bA	1.8bA	2.4bA	1.8bA
EONR	7.9aA	3.7abB	2.7bB	2.6bB
336	9.0aA	5.7aB	10.3aA	4.4bB
	Previous crop = soybean; 16 site-years			
0	4.1cA	2.2cB	1.5cB	1.3cB
EONR	5.5bA	3.2bB	3.2bB	2.3bB
280	10.4aA	10.7aA	6.6aB	4.8aC

† Different lowercase letters in the same column and different uppercase letters in the same row under a previous crop indicate significant N rate and soil depth effects, respectively, at α = 0.05.

‡ EONR (economically optimal nitrogen rate) was 171, 93, and 122 kg ha^{-1} when the previous crop was corn, drybean, and soybean, respectively.

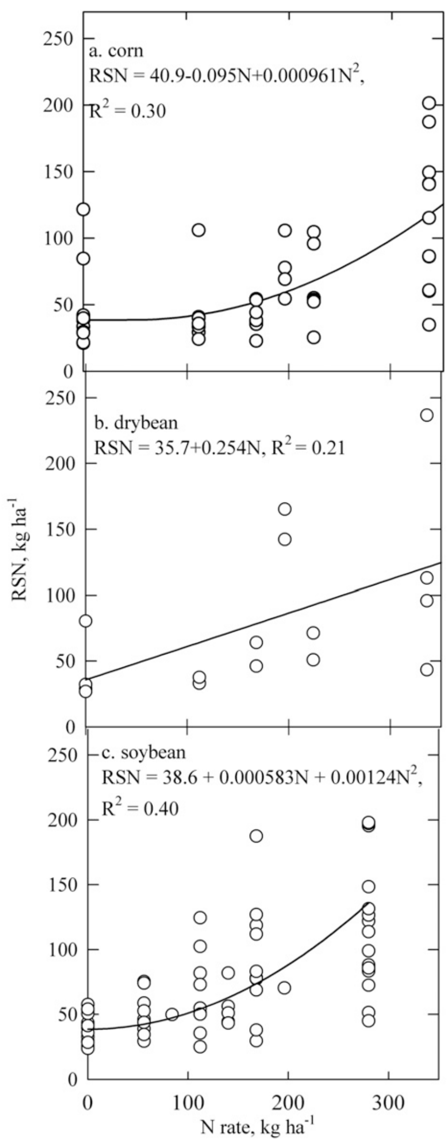

Fig. 4. Mean residual soil NO_3-N following harvest for 32 irrigated corn trials conducted in Nebraska where the previous crop was (a) corn, (b) drybean, and (c) soybean.

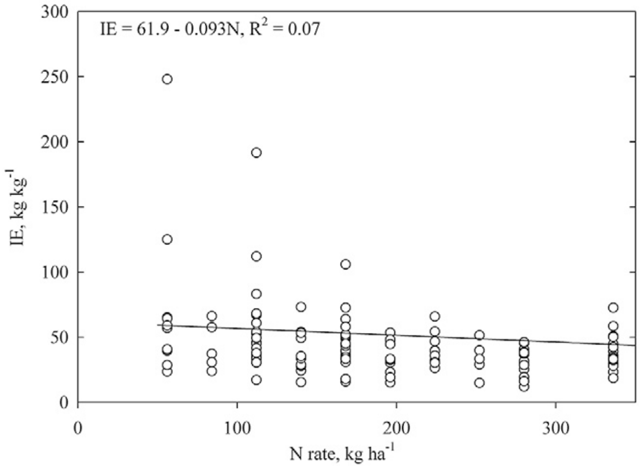

Fig. 5. Mean internal efficiency (IE) of indigenous soil plus fertilizer N, or increases in grain yield relative to increases in plant N accumulated, for 32 irrigated corn trials conducted in Nebraska.

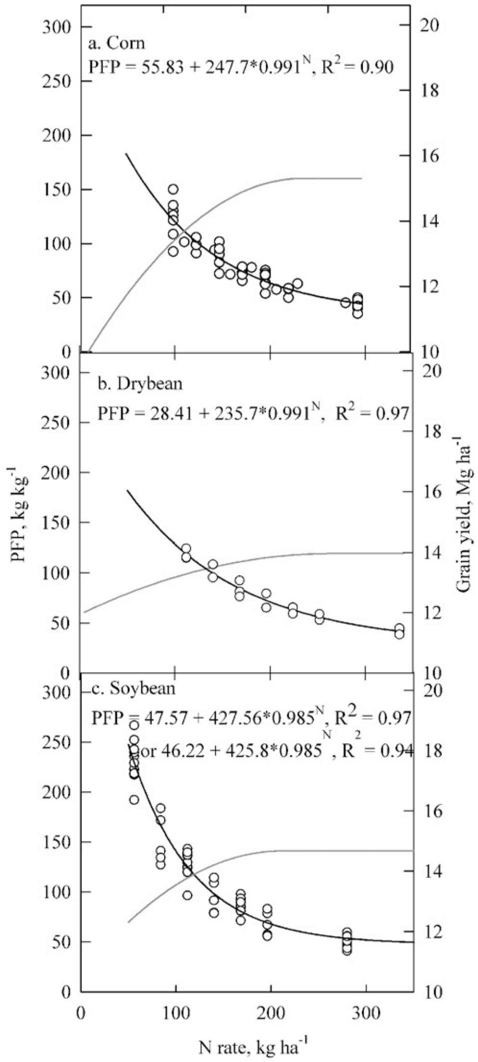

Fig. 6. Mean partial factor productivity (PFP), or grain yield per unit of fertilizer N applied, for 32 irrigated corn trials conducted in Nebraska where the previous crop was (a) corn, (b) drybean, and (c) soybean. The second soybean equation was estimated with three trials that had >50 kg NO_3–N applied in irrigation water excluded; the curve is for the first equation. The gray lines and second y axis are for grain yield (Mg ha^{-1}) response to applied N according to response functions reported in Dobermann et al. (2011).

Table 3. Mean incremental grain and biomass yield efficiency of applied N by irrigated corn at four N rates.

N rate	Grain	Biomass
kg ha^{-1}	–kg yield kg^{-1} N–	
	Previous crop = corn, *n* = 12	
130	29.3	54.5
186	12.2	22.0
242	2.0	4.5
336	2.2	3.7
LSD 0.05	9.2	17.8
	Previous crop = drybean, *n* = 4	
130	10.2	13.7
186	6.7	9.2
242	4.6	26.5
336	0.0	0.0
LSD 0.05	ns†	ns
	Previous crop = soybean, *n* = 16	
74	35.1	60.1
130	16.4	28.3
186	4.3	9.0
280	1.3	2.7
LSD 0.05	9.5	16.4

† ns, no significant effect at α = 0.05.

(Shapiro et al., 2009) accounted for variation in EONR for all cropping systems (Dobermann et al., 2011).

Cropping systems differed for NUE components and increased N rate resulted in decreased NUE components with the exception of NHI which was not significantly affected by N rate. At EONR, CD had high IE, but low AE and RE and high postharvest RSN compared with CS and CC. At N_0, grain yield was high but UN was similar for CD compared with CC and CS (Dobermann et al., 2011; Fig. 1). Two CD site-years had 131 and 254 kg ha^{-1} RSN but grain yield at N_0 was not related to spring RSN (Dobermann et al., 2011). However, many factors affect UN and grain yield and the results from four CD site-years are not sufficient to conclude that spring RSN did not affect response to applied N, RE, and AE. Mean grain yield at EONR and yield response to applied N was less with a low slope for CD compared with CC and CS (Dobermann et al., 2011) which accounts for the low AE and RE, including at the lowest N application rate and EONR. Less preplant application of N and in-season N application for CD based on the condition of the crop may result in increased AE and RE and reduced postharvest RSN.

Compared with CC, PFP was high for CS and CD at EONR (Table 1), probably because of the previous crop effect with less N immobilization compared with corn stover. Over all N rates, PFP remained relatively high for CS but the difference with CC decreased with increased N rate (Fig. 6). These PFP levels are very high compared with the estimated 40 kg kg^{-1} globally (Raun and Schepers, 2008) and of 58 kg kg^{-1} for U.S. corn (Dobermann and Cassman, 2002), but comparable to a range of 81 to 136 for one site and high compared to 53 to 65 for another site in Nebraska (Ping et al., 2008).

High RE is important to reduced RSN that might be lost from the rooting zone by leaching or denitrification (Oberle and Keeney, 1990). Greatly increased postharvest RSN was associated with N rates in excess of EONR and with RE <0.5 (Table 2, Fig. 3 and 4). Recovery efficiency at EONR in this study was high

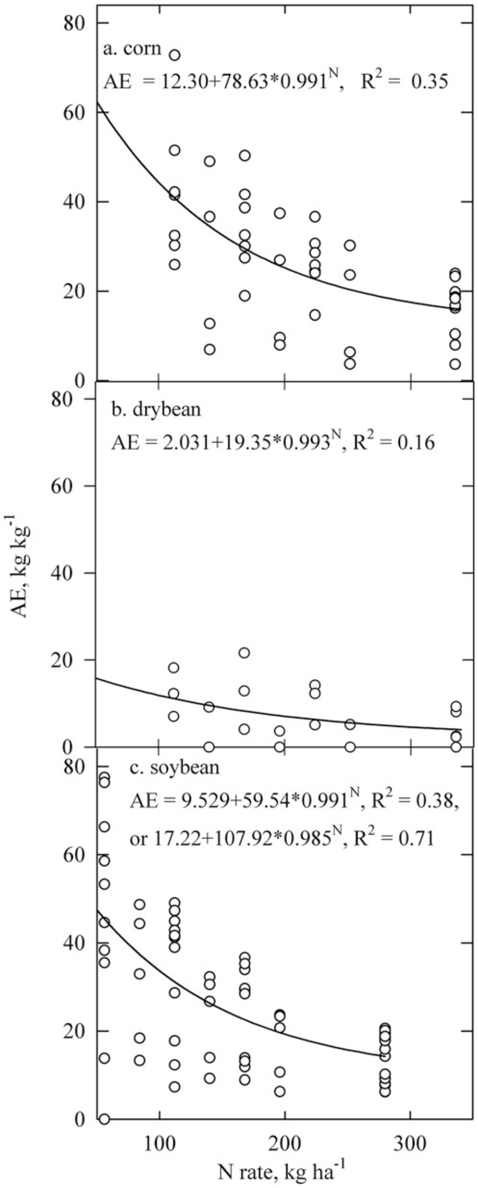

Fig. 7. Mean agronomic efficiency (AE), or increase in grain yield per unit of fertilizer N applied, for 32 irrigated corn trials conducted in Nebraska where the previous crop was (a) corn, (b) drybean, and (c) soybean. The second soybean equation was estimated with three trials that had >50 kg NO_3–N applied in irrigation water excluded; the curve is for the first equation.

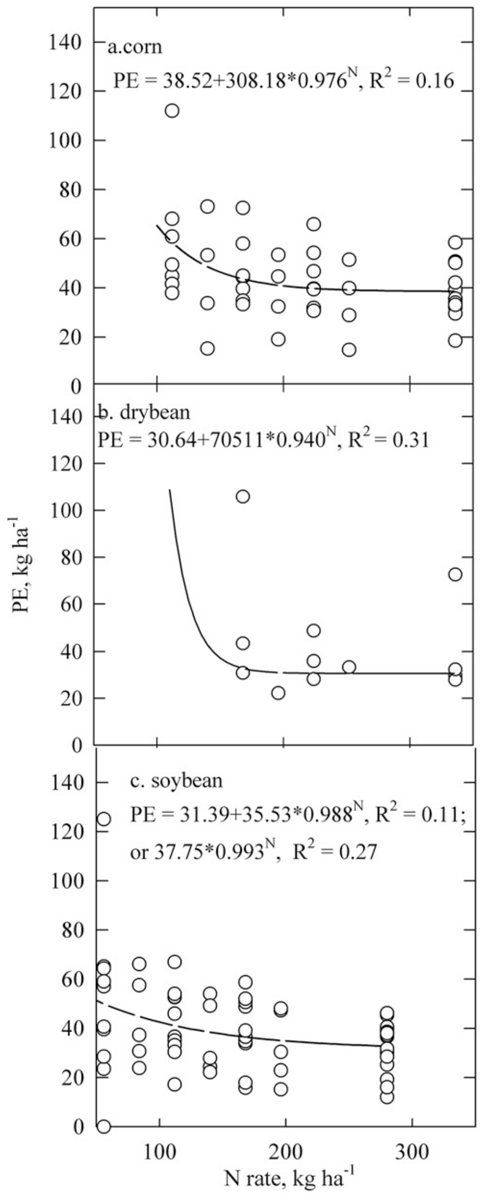

Fig. 8. Mean physiological efficiency of fertilizer nitrogen use (PE) or increases in grain yield (Dobermann et al., 2011) relative to increases in fertilizer N accumulated for 32 irrigated corn trials conducted in Nebraska.

compared to other studies, and the mean for CC and CS was 10 to 198% and 35 and 242% higher than the ranges reported by Oberle and Keeney (1990) and Sanchez and Blackmer (1988), respectively. Recovery efficiency at EONR in our study was high in CC and CS, but relatively low for CD and comparable to the low ends of the ranges reported in these two studies.

Apparent RE can exceed 100% as occurred at some of our site-years and as reported by Motavalli et al. (1992), possibly from increased root growth and/or mineralization of organic N. The results of Motavalli et al. (1992) illustrate the importance of good growing conditions to RE with RE of 14 and 104% in a low and high yielding year, respectively. Seo et al. (2006) reported recovery of 46% of side-dress applied N compared with 32% of preplant applied N. Vetsch and Randall (2004) reported a mean apparent RE of 74% over 3 yr for corn following soybean, a reduction from 87 to 45% for spring compared with fall applied N in a year with wet spring weather, and no tillage effects on RE. Varvel and Peterson (1990) reported higher RE when the previous crop was soybean (52–59%) compared with corn (43–50%), agreeing with our results. Lord and Mitchell (1998) found an RE of 0.52 to be an inflection point below which there was a substantially increased rate of RSN accumulation. The postharvest RSN for CC was generally less than for CD because of more RSN in the surface 30 cm of soil with CD, suggesting that N uptake ceased earlier and/or that more late season mineralization of organic N occurred with CD compared with CC. Cropping system effect was significant with lower RE for CD compared with CS and CC, even at EONR, although CD had the lowest EONR (Table 1).

Opportunity to improve IE may be less compared with RE, AE, and PFP which varied more widely and were more affected by cropping system and N rate. Variation in IE was more due to variation in grain N concentration compared with NHI, indicating a trade-off between improving IE with less grain protein. The higher IE with low N rate was also associated with less grain protein as NHI was not affected by N rate. More variation in IE across site-years was accounted for by NHI at high N rates ($r = 0.64$) compared with N_0 ($r = 0.45$). The higher IE with CD compared with CC, however, was primarily due to difference in NHI, suggesting the CD conditions were more favorable for plant N allocation to grain. An element of IE that is unaccounted for in this study is UN that was lost as NH_3 volatilized from the crop canopy, much of which occurs postanthesis (Francis et al., 1993; Raun and Johnson 1999). More NH_3 volatilization from the crop canopy is expected with higher plant N concentration which increased with increased N rate.

CONCLUSIONS

Across diverse production environments, high corn yields can be achieved with efficient use of soil and applied N and without high risk of NO_3–N leaching to groundwater. With excellent farm management, recovery of applied fertilizer-N in high-yielding corn fields of Nebraska was well above 60 to 70% at EONR, resulting in low RSN levels. Agronomic efficiency and PFP, the NUE components most closely related to profitability of production, can also be high at EONR. Less preplant and more in-season N application may be especially important for CD which had low RE and much postharvest RSN compared with CC and CS. The levels of NUE achieved in our study for CC and CS far exceed current national or regional means, demonstrating the potential for high NUE with high yield corn production. Further NUE efficiency may be gained through more accurate in-season N application such as with use of the presidedress NO_3 test (Andraski and Bundy, 2002) and spatial variation in N rate in response to variation in crop need, such as through use of reflectance sensors (Scharf and Lory, 2009; Barker and Sawyer, 2010; Roberts et al., 2010).

ACKNOWLEDGMENTS

This research was partly supported by the Nebraska State Legislature and the Nebraska Agricultural Business Association. We are grateful for the technical support provided by D. Scoby, G. Slater, D. Binder, G. Teichmeier, J. Peterson, and other research technologists. The cooperation of many producers and farm managers was important to this work. Professor S. Kachman provided valuable guidance in statistical analysis.

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