Nitrogen Response and Economics for Irrigated Corn in Nebraska

A. Dobermann, C. S. Wortmann,* R. B. Ferguson,
G. W. Hergert, C. A. Shapiro, D. D. Tarkalson, and D. T. Walters

ABSTRACT

Nitrogen management recommendations may change as yield levels and efficiency of crop production increase. The mean yield with nutrients applied in 32 irrigated corn (*Zea mays* L.) trials conducted across Nebraska from 2002 to 2004 to evaluate crop response to split-applied N was 14.8 Mg ha^{-1}. The mean economically optimal nitrogen rates (EONR) for irrigated corn varied with the fertilizer N/grain price ratio. At a fertilizer N/corn price ratio of 7 the EONR was 171, 122, and 93 kg ha^{-1}, respectively, for cropping systems with corn following corn (CC), soybean [*Glycine max* (L.) Merr.] (CS), and drybean (*Phaseolus vulgaris* L.) (CD). At this price ratio the present University of Nebraska (UNL) recommendation procedure gave mean N recommendations that were 17.2 and 68.1 kg ha^{-1} higher than the mean EONR determined in this study for CC and CD, respectively, but essentially equal to mean EONR for CS. The UNL algorithm, adjusted for mean cropping system EONR gave more accurate prediction of site-year EONR than alternative N rate predictions for CC and CD with returns to applied nitrogen (RTN) of –\$22 and –\$13 ha^{-1} compared with measured site-year EONR. Prediction of site-year EONR using mean EONR adjusted for soil organic matter was more accurate for CS than other methods with an RTN of –\$6 ha^{-1} compared with measured site-year EONR. Further research is needed to extend the results to: lower yield situations, alternatives to split application of N, and adjustment of EONR to protect against inadequate N in atypical seasons or for environmental protection.

NITROGEN INPUT is generally required to optimize production and economic returns of high yield corn production. Proper management of fertilizer N in these systems is required for profitability and environmental protection associated with N losses. The University of Nebraska–Lincoln's algorithm for estimating nitrogen fertilizer recommendations in corn (UNL-N$_{2000}$) predicts the amount of applied N needed as a function of crop N required for an expected grain yield (EY), soil organic matter (SOM), residual soil nitrate nitrogen content (RSN) in a soil depth of 0.6 to 1.2 m, and other N credits such as previous crop and supplied from manure and irrigation (Ferguson et al., 2000). The UNL-N$_{2000}$, after converting to SI units, is:

$$\text{N rate (kg ha}^{-1}) = 35 + (21.4\ \text{EY}) - (0.223\ \text{EY} \times \text{SOM}) - (9\ \text{NO}_3\text{–N}) - \text{other N credits,}$$

where EY = expected yield (Mg ha^{-1}) where EY = 1.05 5-yr mean yield; NO$_3$–N = root zone soil residual RSN in 60- to 120-cm depth, depth-weighted mean concentration (mg kg^{-1}), and SOM in 0- to 20-cm depth (g kg^{-1}) with a minimum of 10 and a maximum of 30 g kg^{-1}. A previous crop credit is given for soybean but not for dry bean.

The coefficients in UNL-N$_{2000}$ were derived from regression analysis of 81 site-years of N rate irrigated and rainfed trials conducted in Nebraska during 1976 to 1982. Results of on-farm demonstration plots have generally validated UNL-N$_{2000}$, but there were also situations of over- or underestimation of N needs for maximizing profit (Ferguson et al., 1991). Most of the original N response trials were conducted in eastern Nebraska with mean yields of 6.4 and 9.6 Mg ha^{-1} for rainfed and irrigated corn, respectively. Since then, hybrids have changed for N use efficiency (Duvick, 2005), yields have risen by a mean of 0.11 Mg ha^{-1} yr^{-1}, tillage practices have changed, crop management practices have improved, and fertilizer-N use efficiency in corn has increased (Dobermann and Cassman, 2002). Most irrigated corn in Nebraska is produced in continuous corn systems (CC) or in rotation with soybean (CS), while corn following dry bean (CD) is common in the western Nebraska Panhandle. Irrigated corn yield potential in Nebraska commonly ranges from 13 to 19 Mg ha^{-1} (Dobermann et al., 2003; Dobermann and Shapiro, 2004; Grassini et al., 2009). The changes in management practices and corn hybrids, and the increases in corn yields across the diverse production areas of Nebraska, since UNL-N$_{2000}$ was formulated justified re-evaluation of the algorithm.

The conceptual basis of UNL-N$_{2000}$ was well supported by research conducted elsewhere. Oberle and Keeney (1990) estimated that 35 kg Mg^{-1} of SOM–N was mineralized annu-

---

A. Dobermann, International Rice Research Institute, Los Baños, Laguna, Philippines. C.S. Wortmann, R.B. Ferguson, G.W. Hergert, C.A. Shapiro, D. Walters (deceased), Dep. of Agronomy and Horticulture, 279 Plant Science, Univ. of Nebraska, Lincoln, NE 68583–0915. D.D. Tarkalson, Northwest Irrigation and Soils Research Lab., Kimberly, ID. Contribution of the University of Nebraska–Lincoln Agricultural Research Division. This research was partly funded by the Hatch Act and the Nebraska State Legislature. Received 16 Apr. 2010. *Corresponding author (cwortmann2@unl.edu).

Published in Agron. J. 103:67–75 (2011)

doi:10.2134/agronj2010.0179

Abbreviations: CC, CD, CS, cropping systems in which the previous crop was corn, dry bean and soybean, respectively; EONR, economically optimal nitrogen rate; EY, expected yield; RSN, residual soil nitrate nitrogen, mg kg^{-1}; RTN, returns to applied nitrogen or gross returns minus returns with no nitrogen applied minus the cost of nitrogen (\$ ha^{-1}); SOM, soil organic matter; UNL-N$_{2000}$, the corn nitrogen rate determined with University of Nebraska–Lincoln algorithm in Ferguson et al. (2000).

ally. This compares to 15 to 35 kg Mg^{-1} from UNL-N_{2000} with credit increasing as grain yield potential increases.

Vanotti and Bundy (1994) found that RSN was used as efficiently as fertilizer N and could be credited similar to fertilizer N if the nitrate N was not lost to excessive leaching and denitrification. They found that for continuous corn, the relationship between optimum fertilizer N rate (Y) and RSN was Y = 193 – 0.88 RSN when the amount of RSN was between 45 and 195 kg ha^{-1} in the upper 90 cm of soil. When RSN concentration is <3 mg kg^{-1}, RSN may not be efficiently used (Bundy and Malone, 1988; Schepers and Mosier, 1991). The UNL-N_{2000} credits approximately 50% of the RSN in 1.2-m soil depth.

Use of yield goal in an algorithm is supported by Franzleubbers et al. (1994) who determined that N required, from all sources, to attain 95% of maximum predicted yield for continuous corn was10.4 kg N Mg^{-1} of grain yield. Vanotti and Bundy (1994) found, however, that optimum N rate did not vary with corn yield, suggesting improved N use efficiency with increased corn yield.

The actual N credit or N replacement value for corn following soybean varies. Varvel and Wilhelm (2003) reported a mean N credit of 65 kg ha^{-1} for the irrigated soybean–corn rotation in Nebraska. Bergerou et al. (2004) determined a mean N replacement value for corn following soybean of 83 kg ha^{-1}. Given this and the potential for yield loss with underapplication of N, the credits used in determining N rates tend to set a conservatively low value, such as 50 kg ha^{-1} in Nebraska (Ferguson et al., 2000; Shapiro et al., 2009).

The objectives of this research were to quantify the yield response of corn to N at high yield levels that exceeded those in most previously published studies and develop alternatives for estimating site-year EONR for irrigated corn at different N/corn price ratios.

MATERIALS AND METHODS

Site Characteristics, Treatments, and Experimental Design

Trials to determine corn response to N at 32 site-years were conducted representing the main corn production areas of Nebraska from 2002 to 2004. The site-years included 13 on research stations and 19 in producers' fields, and 10, 9, and 13 site-years were no-till, ridge till, and either disk or chisel plow tillage, respectively. There were 12, 16, and 4 site-years, respectively, for CC, CS, and CD. The CS site-years were primarily in eastern Nebraska and all no-till site-years were CS. The CC site-years were primarily in south central and west central Nebraska, and all of the ridge-till site-years were CC. The CD site-years were in the west and were disk or chisel plow tilled. Therefore, there was confounding of location, tillage practice, and previous crop. Thus, CC, CS, and CD represent more than previous crop effects and are generalizations of three important corn production systems in Nebraska.

The soils varied with site and included Agriudolls (Tomek, Wymore), Agriustolls (Holdrege, Hall, Hastings, Crete), Hapludolls (Kennebec), Ustorthents (Crofton), Haplustolls (Hord, Cozad, Vetal, Creighton, Thurman, Moody, Nora), and Torriorthents (Mitchell) (Table 1). Soil texture ranged from silty clay loam to loamy sand. Rooting depth was always > 1 m. Soil at each site was sampled before planting at the 0- to 0.2-m depth, air-dried, sieved (2 mm), and analyzed for SOM by loss on ignition, $pH_{1:1}$, Bray-1 P, exchangeable K, and SO_4–S (NCR-13, 1998). Soil was also sampled to a depth of 1.2 m in 0.3 m segments in the spring before planting and analyzed for nitrate N (NCR-13, 1998). SOM ranged from 7 to 34 g kg^{-1} and soil pH ranged from 4.8 to 7.5 (Table 1). Mean Bray-1 P ranged from 5 to 88 mg kg^{-1} and soil available K was generally high and >125 mg kg^{-1} (Shapiro et al., 2009). Bray-1 P was below 15 mg kg^{-1} at 38% of the sites and available soil K was below the critical level of 125 mg kg^{-1} at three sites only. Further discussion of response to P, K, and S is provided elsewhere (Wortmann et al., 2009).

The five N rates were 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. Lower N rates were applied in the first year of the study, and the higher rates were applied in the second and third study years to better capture the response function. Fertilizer P and K were applied to all plots at rates of 20 and 40 kg ha^{-1}, respectively, to ensure adequate levels for optimal crop performance (Wortmann et al., 2009). Fertilizer was broadcast either with plot spreaders or by hand. Forty to 60% of N was applied preplant, with the remainder side-dress applied at V6 (Ritchie et al., 1996) for medium and fine texture soils and at V6 and V10 for sandy soils. The fertilizers were ammonium nitrate (34-0-0), triple superphosphate (0-20-0), and muriate of potash (0-0-50). No starter fertilizer was used. Sulfur was applied as calcium sulfate for nine site-years when potential for S deficiency was suspected.

Individual plots were at least 6.1 m or wider and 15.2 m long. Plots were arranged in a randomized complete block design with four replications at each site.

Seeding rates were selected to ensure final plant populations of seven to eight plants m^{-2}. All locations were irrigated. Tillage, weed and pest control, and time and amounts of irrigations were managed by the cooperator at each site. Hybrids of proven yield potential and adaptation were selected with the cooperating farmer.

Grain yield was determined from two 6.1-m row segments. Yields were adjusted to 155 mg kg^{-1} grain water content.

Data Analysis

The analyses were done using Statistix 9 (Analytical Software, Tallahassee, FL) except for the N response functions which were determined for N rate means by site-year using SigmaPlot 10.0 (Systat Software, Chicago, IL). Grain yield was plotted against N rate and, after evaluating several models, two response functions that give a quadratic plus plateau response were fitted for each site-year. For each model, the EONR needed to achieve maximum net return from N application was calculated based on mathematical differentiation of the fitted equations for a range of different N/corn price ratios:

(1) Exponential rise to a maximum (modified Mitscherlich equation):

$$Y = a + b(1 - e^{-cN})$$

$$\mathrm{EONR} = \frac{1}{-c}\ln\left(\frac{1/\mathrm{R}}{bc}\right) \quad \text{for} \quad \frac{1}{-c}\ln\left(\frac{1/\mathrm{R}}{bc}\right) > 0$$

$$= 0 \qquad \text{for} \quad \frac{1}{-c}\ln\left(\frac{1/\mathrm{R}}{bc}\right) \le 0$$

where a = yield without N application, b = maximum yield increase from applying N (ΔY at max N rate), c = curvature

Table 1. Site characteristics for 32 irrigated corn trials conducted in Nebraska.

Site-year	Soil†	Texture‡	Till‡	SOM	Soil pH	Irrigation NO_3–N Applied	Soil NO_3–N in 1.2 m	
							Spring	Fall
				g kg^{-1}		kg ha^{-1}		
				Cropping system = corn–corn				
Bellwood03	Hord	sil	RT	24	6.7	24	137	29
Brosius04	Hord	sl	CT	10	4.8	8	75	43
Cairo02	Hall	sil	RT	25	7.1	19	50	38
Cairo03	Holdrege	sil	RT	28	6.8	16	48	121
Cairo04	Hord	sil	RT	24	6.7	15	53	22
Clay Center02	Hastings	sil	RT	29	6.9	28	59	42
Funk04	Holdrege	sil	RT	28	6.8	11	83	29
N.Platte02	Cozad	sil	RT	20	7.3	11	50	34
N.Platte03	Hord	sl	CT	10	4.8	2	103	30
Paxton02	Vetal	ls	CT	13	6.3	34	58	40
Paxton03	Vetal	ls	CT	20	6.3	30	39	21
Spurgin04	Vetal	ls	CT	20	6.3	5	94	30
				Cropping system = soybean–corn				
Brunswick02	Thurman	ls	NT	7	6.5	56	30	29
Brunswick03	Crofton	sil	NT	19	6.8	42	83	36
Brunswick04	Thurman	ls	CT	9	6.3	60	60	43
Concord02†	Nora	sil	NT	33	5.8	29	37	29
Concord03	Nora	sil	NT	30	5.8	32	109	46
Concord04	Kennebec	sil	NT	28	6.4	40	160	56
Mead02	Tomek	sicl	NT	31	6.2	90	47	54
Mead03	Tomek	sil	NT	30	6.4	11	56	23
Mead04	Tomek	sicl	NT	34	6.3	19	50	34
North Bend04	Moody	sicl	CT	30	6.4	18	77	47
Pickrell03	Wymore	sicl	NT	29	5.8	22	51	27
Pickrell04	Wymore	sicl	NT	28	6.2	16	48	50
SCAL02	Crete	sil	CT	30	6.1	28	70	29
SCAL03	Crete	sil	CT	33	6.6	10	87	25
SCAL04	Crete	sil	CT	26	6.9	8	66	31
Wymore02	Wymore	sicl	NT	27	6.3	16	36	25
				Cropping system = drybean–corn				
Box Butte03	Creighton	sil	CT	17	7.3	17	73	29
Box Butte04	Creighton	sil	CT	16	7.5	13	62	27
Scottsbluff02	Mitchell	sl	CT	17	7.3	10	254	32
Scottsbluff03	Mitchell	sl	CT	27	7.1	12	131	97

† Soil orders included Agriudolls (Tomek, Wymore), Agriustolls (Holdrege, Hall, Hastings, Crete), Hapludolls (Kennebec), Ustorthents (Crofton), Haplustolls (Hord, Cozad, Vetal, Creighton, Thurman, Moody, Nora), and Torriorthents (Mitchell).

‡ Soil texture classes include: ls, loamy sand; sl, sandy loam, sil, silt loam; and sicl, silty clay loam. Tillage alternatives include: CT, conventional tillage; NT, no-till; and RT, ridge till.

coefficient, N = N rate (kg N ha^{-1}), and R = ratio corn price (\$ Mg^{-1})/N price (\$ kg^{-1}).

(2) Spherical model (linear + nonlinear rise to a plateau):

$$Y = a + b\left\{\frac{3N}{2c} - \frac{1}{2}\left(\frac{N}{c}\right)^{3}\right\} \quad \text{for} \quad 0 \le c$$

$$= a + b \qquad \text{for} \quad 0 > c$$

$$\text{EONR} = \sqrt{\frac{1.5bc^{2} - \frac{c^{3}}{\text{R}}}{1.5b}} \quad \text{for} \quad \left(1.5bc^{2} - \frac{c^{3}}{\text{R}}\right) > 0$$

$$= 0 \qquad \text{for} \quad \left(1.5bc^{2} - \frac{c^{3}}{\text{R}}\right) \le 0$$

where a = yield without N application, b = maximum yield increase from applying N (ΔY at max N rate), c = N rate at which maximum yield occurred, N = N rate (kg N ha^{-1}), and R = ratio corn price (\$ Mg^{-1})/N price (\$ kg^{-1}). While EONR was calculated with R, the N/corn price ratio (\$ kg^{-1})(\$ kg^{-1})$^{-1}$ is used through the remainder of the paper for easier comprehension of the price factor.

Both models accounted for >60% of the variation in treatment means by site-year, with the exception of the spherical model at Scottsbluff in 2003 (Table 2), but they differed in shape and, therefore, in their sensitivity to price changes and the derived EONR. Because the exponential model is more gradual in shape, slowly approaching the maximum yield, it also results in a wider range of the EONR as the N/corn price ratio increases or decreases (Fig. 1). Since regression fit statistics alone made it difficult to justify choosing a single model as superior, we opted to use the average EONR derived from both models in further statistical analysis and adjustment of N recommendations. This reduces potential errors associated with the choice of a particular model.

Using the means of the two response functions, EONRs, grain yield and RTN at EONR were determined for each site-year for N/corn price ratios of 5, 7, 9, 11, and

Table 2. Coefficients for two functions applied to irrigated corn yield response to applied N for 32 irrigated trials conducted in Nebraska.

Irrigated trials	Max.†	Exponential rise to a maximum (modified Mitscherlich): Y (Mg ha^{-1}) = $a + b(1 - e^{-cN})$†					Spherical model (linear + nonlinear rise to a plateau): Y (Mg ha^{-1}) = $a + b[3N/2c - (N/c)^3/2]$ if $(c - N) \geq 0$; else $Y = a + b$				
		a	b	c	SE	R^2	a	b	c_{SM}	SE	R^2
	Mg ha^{-1}	Mg ha^{-1}	Mg ha^{-1}		Mg ha^{-1}		Mg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}	
Cropping system = corn–corn											
Bellwood03	17.78	12.73	4.71	0.007	0.29	0.85	13.46	3.39	364.7	0.25	0.88
Brosius04	12.40	5.62	6.61	0.017	0.58	0.96	5.62	6.41	194.3	0.28	0.99
Cairo02††	14.13	10.99	1.91	0.027	0.03	1.00	10.99	1.90	178.0	0.04	1.00
Cairo03	17.51	8.65	8.26	0.038	0.32	0.99	8.66	8.17	105.8	0.32	0.99
Cairo04	16.81	10.49	7.24	0.008	0.24	0.99	10.56	6.20	292.7	0.20	0.99
Clay Center02	15.02	7.01	8.00	0.017	0.15	1.00	7.00	7.67	153.9	0.35	0.99
Funk04	16.13	10.52	5.66	0.020	0.17	1.00	10.53	5.50	169.8	0.12	1.00
N.Platte02	15.19	8.71	6.62	0.012	0.31	0.99	8.75	6.08	242.3	0.56	0.95
N.Platte03	14.64	8.76	6.05	0.011	0.48	0.96	8.76	5.55	237.6	0.20	0.99
Paxton02	15.41	13.83	1.22	0.022	0.34	0.65	13.83	1.23	205.3	0.32	0.70
Paxton03	16.22	8.79	6.96	0.023	0.38	0.98	8.82	6.85	169.8	0.18	1.00
Spurgin04	14.17	10.71	3.44	0.020	0.07	1.00	10.71	3.32	160.7	0.15	0.99
Mean	15.45	9.73	5.56	0.019	0.28	0.95	9.81	5.19	206.2	0.25	0.96
SD	1.54	2.29	2.29	0.010	0.16	0.10	2.39	2.23	69.65	0.13	0.09
Cropping system = soybean–corn											
Brunswick02	13.15	9.09	4.25	0.017	0.18	0.99	9.12	4	172.3	0.08	1.00
Brunswick03	16.32	10.61	5.70	0.017	0.19	0.99	10.68	5.19	150.7	0.39	0.97
Brunswick04	12.08	9.96	2.68	0.009	0.17	0.97	10.00	2.26	236.7	0.01	1.00
Concord02	12.11	9.76	1.73	0.033	0.01	1.00	9.76	1.71	113.7	0.04	1.00
Concord03	14.44	12.68	1.78	0.016	0.08	0.99	12.69	1.66	189.8	0.18	0.95
Concord04	15.34	12.14	2.71	0.037	0.52	0.82	12.16	2.72	103.5	0.45	0.86
Mead02	15.52	13.31	2.50	0.011	0.20	0.95	13.31	2.19	209.2	0.17	0.98
Mead03	14.67	7.71	6.97	0.034	0.16	0.99	7.71	5.48	134.4	0.80	0.89
Mead04	15.52	9.71	5.59	0.025	0.48	0.96	9.89	5.32	134.4	0.59	0.94
North Bend04	14.40	11.48	2.41	0.039	0.43	0.84	11.47	2.35	74.9	0.45	0.83
Pickrell03	13.96	7.91	5.82	0.030	0.06	1.00	7.92	5.67	99.3	0.14	1.00
Pickrell04	16.62	10.56	5.44	0.020	0.45	0.96	10.71	5.05	150.2	0.12	1.00
SCAL02	16.29	11.73	4.55	0.026	0.10	1.00	11.74	4.44	102.4	0.15	0.99
SCAL03	17.05	11.7	5.08	0.023	0.05	1.00	11.76	4.76	123.2	0.37	0.97
SCAL04	15.93	10.22	5.78	0.019	0.73	0.90	10.21	5.45	144.8	0.40	0.97
Wymore02	12.38	6.62	4.93	0.024	0.22	0.99	6.62	4.77	124.5	0.32	0.98
Mean	14.81	10.40	4.17	0.023	0.27	0.96	10.45	3.94	141.49	0.29	0.96
SD	1.65	1.77	1.57	0.009	0.212	0.057	1.8	1.5	43.0	0.22	0.053
Cropping system = drybean–corn											
Box Butte03	15.54	11.91	3.28	0.016	0.66	0.78	11.87	3.17	193.6	0.55	0.85
Box Butte04	13.31	12.19	0.75	0.029	0.07	0.95	12.20	0.74	91.30	0.07	0.95
Scottsbluff02	13.52	12.11	1.30	0.029	0.04	1.00	12.11	1.28	114.2	0.03	1.00
Scottsbluff03	14.58	13.02	1.68	0.005	0.42	0.61	13.02	1.20	158.0	0.45	0.36
Mean	14.24	11.83	2.67	0.020	0.37	0.89	11.80	2.44	188.5	0.29	0.93
SD	1.07	0.32	1.37	0.010	0.30	0.09	0.34	1.19	76.16	0.20	0.06

† Max. = mean yield for highest yield treatment for the site-year; a = yield at 0 kg N; b = maximum yield increase from N application; c = curvature coefficient; and SE = standard error of predicted yield; and c_{SM} = N rate in spherical model at which the yield plateau begins.

13 (\$ kg^{-1})(\$ kg^{-1})$^{-1}$. The mean EONR, yield at EONR, and RTN at EONR, and their LSD 0.05, were determined for CC, CS, and CD. Linear regression analysis was applied to determine the relationships of EONR to price ratio using the cropping system mean EONR for each price ratio. Regression analysis was also used to evaluate variation in site-year SOM, RSN for four soil depths, N applied in irrigation water, and maximum treatment yield for efficiency in improving the prediction of site-year EONRs of each cropping system.

Four alternatives were evaluated for accuracy in predicting EONR and determining N rate with minimal loss of RTN. (i) The UNL-N$_{2000}$, which had no adjustments for N/corn price ratio, was calculated using site-specific input data for expected yield based on past yields and known site yield potential, SOM (0- to 20-cm depth), RSN in the spring to 1.2 m depth, N credits for previous crop, and N input from irrigation water. (ii) The UNL-N$_{2000}$ adjusted N rate (UNL-N$_{2000\mathrm{adj}}$) was determined by multiplying site-year UNL-N$_{2000}$ by mean EONR divided by mean UNL-N$_{2000}$ for each N/corn price ratio with the result that mean UNL-$N_{2000adj}$ equaled mean EONR. (iii) The mean EONR for each cropping system was used. (iv) The mean EONR adjusted for SOM ($EONR_{SOM}$) was used for CS. The respective predicted EONRs were determined for each site-year. Grain yields for the predicted EONRs were determined from the N response curves for each site-year. The mean differences of predicted minus measured site-year EONR were calculated for grain yield and RTN at five N/corn price ratios and for each crop system with LSD 0.05 representing variation across site-years. Functions were determined for converting UNL-N_{2000} to UNL-$N_{2000adj}$ for a continuous range of N/corn price ratios.

RESULTS

Corn Yield Response to Nitrogen

The maximum treatment yield ranged from 12.1 to 17.8 Mg ha^{-1}, including 18 site-years with maximum treatment yield >15 Mg ha^{-1}, and a mean of 14.8 Mg ha^{-1} (Fig. 1, Table 2). Maximum treatment yield <13.2 Mg ha^{-1} occurred for only 5 of the 32 site-years with several possible contributing factors including insect problems, acid pH in a sandy soil, insufficient irrigation, low plant population, early season low temperature stress, S deficiency during early growth on a sandy soil, or late maturity because of low temperatures. The generally high maximum grain yields, attributed to adequate nutrient supply and excellent management, approached the climatic-genetic yield potential for the study locations (Dobermann et al., 2003).

Yield with no N applied ranged from 5.6 to 13.8 Mg ha^{-1} with CC having more variation, and CD having less variation, compared with CS (Table 2; Fig. 2). Mean yield with no N applied was greatest for CD and least for CC. The yield increase due to N application ranged from 0.7 to 8.3 Mg ha^{-1} and from 9 to 120% of the yield with no N applied. The mean yield increase was greatest and most variable for CC and least and least variable for CD with respective mean increases of 66 and 20% of the yield with no N applied. The N rate at the beginning of the yield response plateau ranged from 75 to 365 kg ha^{-1} and was 65 kg ha^{-1} less for CS compared with CC agreeing with the mean soybean N credit determined by Varvel and Wilhelm (2003). Corn response to applied N differed with cropping system where the effects of previous crop were confounded with tillage and location (Table 1). The data set was inadequate to attempt to separate tillage and location effects from previous crop effects.

The exponential rise to maximum yield and the spherical to yield plateau models gave similar mean estimates of yield with no N applied, maximum yield response to applied N, and N rate at which the yield plateau began (Fig. 1). The rate of yield increase with low N rates was predicted to be greater with the exponential rise to maximum yield compared with the spherical to yield plateau model.

Economically Optimal Nitrogen Rates

The mean EONRs for CC, CS, and CD were 171, 122, and 93 kg ha^{-1}, respectively, when the fertilizer N/corn price ratio was 7. The variability in EONR across site-years was greatest for CC and least for CS (Table 3). Expected yield, SOM, RSN, and irrigation nitrate N did not account for variation in EONR across sites for CC and CD (data not shown). The LSD 0.05 of EONR for CS was reduced by considering site-year SOM but not by consideration of other individual factors. However, UNL-N_{2000} was related to EONR at different N/corn price ratios with Pearson coefficients of correlation significant at $P < 0.1$ ranging from 0.52 to 0.59 for CC, 0.43 to 0.66 for CS, and >0.90 for CD at higher N/corn price ratios. Therefore, the index as a whole was predictive of EONR even if its individual factors generally did not account for variation in EONR. The response of EONR to changing N/corn price ratio was linear with similar slopes for CC and CD, and less slope for CS (Fig. 3).

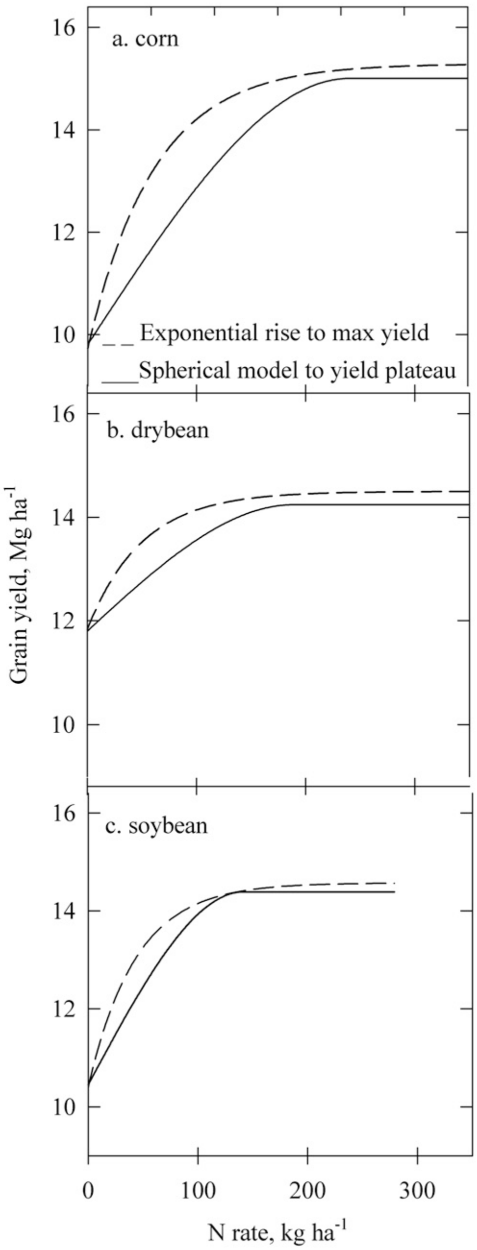

Fig. 1. Mean N response curves estimated for the exponential rise model to maximum yield and spherical model to yield plateau for 32 irrigated corn trials conducted in Nebraska in 2002–2004 where the cropping system was corn following (a) corn (*n* = 12), (b) soybean (*n* = 16), and (c) drybean (*n* = 4).

Mean corn grain yield was approximately 0.3 Mg ha^{-1} less when N was applied at EONR for a N/corn price ratio of 13 compared with 5 (Table 3). The RTN was greatest with CC and least with CD (Fig. 4). The loss in RTN with N applied at EONR ± LSD 0.05 was greater for CC and CD compared with CS when mean EONR was not adjusted, and the loss in RTN was reduced for CS by adjusting EONR by site SOM.

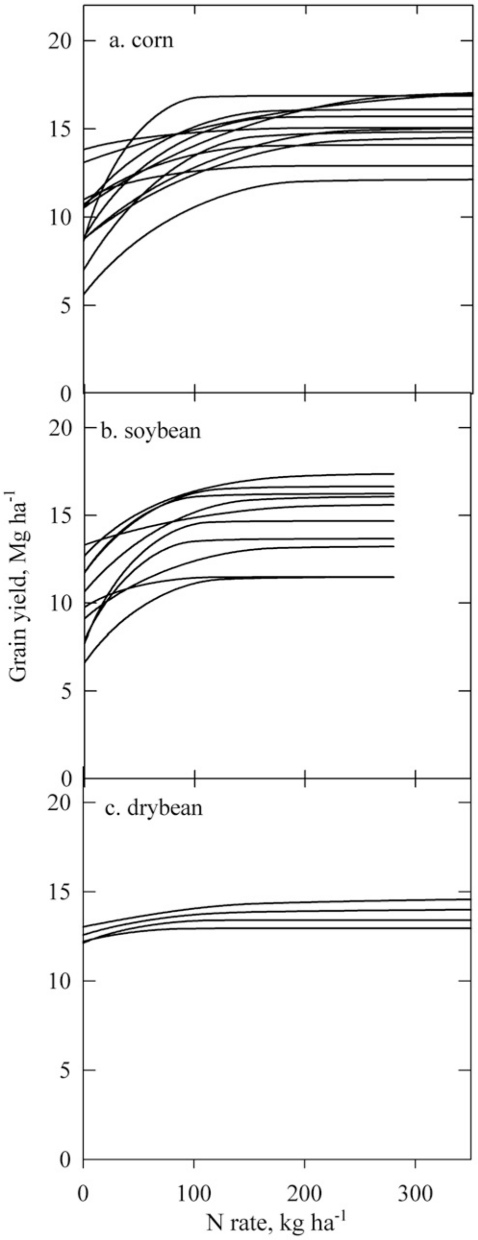

Fig. 2. Nitrogen response curves for 32 irrigated corn trials conducted in Nebraska in 2002–2004 where the cropping system was corn following (a) corn, (b) soybean, and (c) drybean.

Loss in RTN for N applied at EONR ± LSD 0.05 increased for all previous crops as the N/corn price ratio increased.

Prediction of Economically Optimal N Rates

The mean N rate determined by UNL-N_{2000} was generally high compared to EONR, especially for CD and least so for CS (Table 4). The N rate $LSD_{0.05}$ was less for UNL-N_{2000} compared with EONR for CC and CD but greater for CS. Factors for adjusting mean UNL-N_{2000} to mean EONR at different N/corn price ratios varied from 0.75 to 0.95 for CC, 0.83 to 1.05 for CS, and 0.44 to 0.65 for CD. The low EONR compared with UNL-N_{2000} for CD reflects overrecommendation of N for CD using UNL-N_{2000}, suggesting that UNL-N_{2000} should have a previous crop N credit for CD as for CS.

Prediction of EONR using UNL-$N_{2000adj}$ improved prediction of EONR with less loss in RTN compared with UNL-N_{2000}. Accuracy of predicting EONR using UNL-$N_{2000adj}$ was similar to using mean EONR but less accurate than using $EONR_{SOM}$ for CS. Return to N (\$ ha^{-1}), averaged over price ratios, for UNL-N_{2000}, UNL-$N_{2000adj}$, and mean EONR were, respectively, decreased by 40.22, 21.90, and 26.10 for CC ($P = 0.078$); 25.00, 20.96, and 8.92 (5.88 for $EONR_{SOM}$) for CS ($P = 0.035$); and 78.30, 12.76, and 19.72 for CD ($P = 0.002$).

Continuous functions for estimating UNL-$N_{2000adj}$ are:

$$\text{UNL-N}_{2000\text{adj}} \text{ for CC} = \text{UNL-N}_{2000} - (-1.6 + 9.9\ \text{Ratio})\ (R^2 = 1.00);$$

$$\text{UNL-N}_{2000\text{adj}} \text{ for CS} = \text{UNL-N}_{2000} - (-13.2 + 6.9\ \text{Ratio})\ (R^2 = 1.00);$$

and

$$\text{UNL-N}_{2000\text{adj}} \text{ for CD} = \text{UNL-N}_{2000} - (-50.3 + 8.5\ \text{Ratio})\ (R^2 = 0.97);$$

where Ratio = N/corn price ratio.

Table 3. The mean economically optimal nitrogen rates (EONR), yields, and returns to nitrogen (RTN) at EONR, with LSD 0.05, for five N/corn price ratios for irrigated corn in Nebraska.

N rates, yields, and returns	Price of N relative to price of corn, (\$ kg^{-1}) (\$ kg^{-1})$^{-1}$				
	5	7	9	11	13
	Cropping system = corn–corn				
EONR kg ha^{-1}	179.7 ± 40.0	171.1 ± 36.8	160.5 ± 34.0	149.4 ± 31.3	141.5 ± 30.0
$\text{Yield}_{\text{EONR}}$ Mg ha^{-1}	14.9 ± 1.0	14.9 ± 1.0	14.8 ± 1.0	14.7 ± 1.0	14.6 ± 1.0
RTN \$ ha^{-1}	711 ± 152	654 ± 150	602 ± 150	553 ± 151	508 ± 153
	Cropping system = soybean–corn†				
EONR kg ha^{-1}	128.6 ± 15.6	122.0 ± 14.3	114.7 ± 12.7	107.0 ± 11.3	101.8 ± 10.5
$\text{Yield}_{\text{EONR}}$ Mg ha^{-1}	14.5 ± 0.9	14.5 ± 0.9	14.4 ± 0.9	14.4 ± 0.9	14.3 ± 0.9
RTN \$ ha^{-1}	546 ± 149	505 ± 150	467 ± 148	432 ± 148	400 ± 147
	Cropping system = drybean–corn				
EONR kg ha^{-1}	104.4 ± 68.6	93.4 ± 64.8	82.1 ± 64.9	75.7 ± 61.5	70.6 ± 59.7
$\text{Yield}_{\text{EONR}}$ Mg ha^{-1}	13.8 ± 1.5	13.7 ± 1.4	13.7 ± 1.4	13.6 ± 1.4	13.6 ± 1.4
RTN \$ ha^{-1}	138 ± 183	105 ± 163	78 ± 145	55 ± 130	37 ± 116

† When soybean EONR was adjusted in consideration of soil organic matter (EONR = EONR – (SOM – 2.66) * 18), mean LSD 0.05 of EONR was reduced to 7.8.

DISCUSSION

The N response results are presented by cropping system. Cropping systems, distinguished by crop sequence, differed for tillage and geographic location with CS site-years primarily in eastern Nebraska with no-till, CC in south central and west central Nebraska commonly with ridge-till, and CD in western Nebraska with disk or chisel plow tillage. The results are inadequate, and were not intended to be adequate, to separate the effects of tillage, other management practices, and environmental differences associated with site-year from the rotation effects. Mean response to N and EONR differed by crop sequence as others have found (Varvel and Wilhelm, 2003; Bergerou et al., 2004; Ferguson et al., 2000; Shapiro et al., 2009).

Yield with no N applied was high and response to applied N and EONR were low for CD compared with CC and CS (Tables 2 and 3; Fig. 2). Large amounts of RSN before planting for the two Scottsbluff CD site-years (Table 1) may have affected N response and EONR although the response for these two site-years was intermediate compared with the other two CD site-years with much less RSN. Dry bean crop residue decomposes readily with little soil N immobilization and early mineralization of organic N compared with corn residue. The results show that the EONR are low for CD compared with CC but the results were from only four site-years and further research is needed to fine-tune or verify the N rate recommendation for CD.

Some site-years had low soil test P or pH but variation in these variables was not related to variation in grain yield. Phosphorus and K was applied for all site-years ensuring that P and K were not limiting to N response (Wortmann et al., 2009). The lower pH levels were not considered to be corn yield limiting and the results did not give any indication that low pH constrained maximum yield or response to N. The average EONR values in our study were slightly below those reported for a large regional database of rainfed corn grown in other Corn Belt areas (Sawyer and Nafziger, 2005). Higher N use efficiency and hence lower EONR in our study was probably due to generally higher yield levels enabled through adequate water availability with irrigation and preplant combined with sidedress N application to reduce N loss to leaching. Small deviations in N application rate from the EONR generally have little effect on yield or RTN (Fig. 4). The N application rate can be increased to ensure adequate N for exceptionally productive years (Kyveryga et al., 2007), decreased to reduce N losses to water bodies (Sawyer and Randall, 2008), or decreased to reduce energy consumption or N_2O emission without much loss in productivity or RTN. At most N/corn price ratios, there is greater potential for reduced RTN with underapplication compared with overapplication of N relative to EONR (Fig. 4).

The UNL-N_{2000} performed better for CS than for CC and greatly overestimated N need for CD. The UNL-N_{2000} resulted in mean N rates that were close to mean EONR at N/corn price ratios of 5 and 7, excluding CD where the results indicate a need for a previous crop credit with UNL-N_{2000} (Table 4). The UNL-N_{2000}, however, accounted for just 37% of the variation in EONR for CC and CS. Consequently, RTN was less for UNL-N_{2000} compared with actual EONR. Adjustments of recommended N rates according to prices become more important as the N/corn price ratio increases.

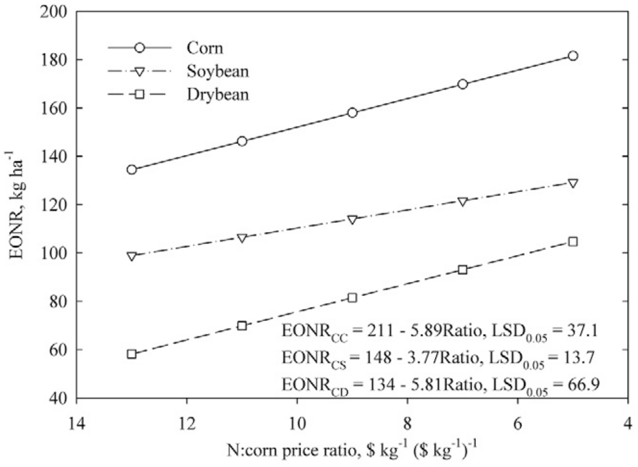

Fig. 3. The effect of the N/corn price ratio on the economically optimal nitrogen rate (EONR) determined for corn following corn (*n* = 12, CC), soybean (*n* = 16, CS), and drybean (*n* = 4, CD) in rotation as determined from 32 irrigated trials conducted in Nebraska in 2002–2004.

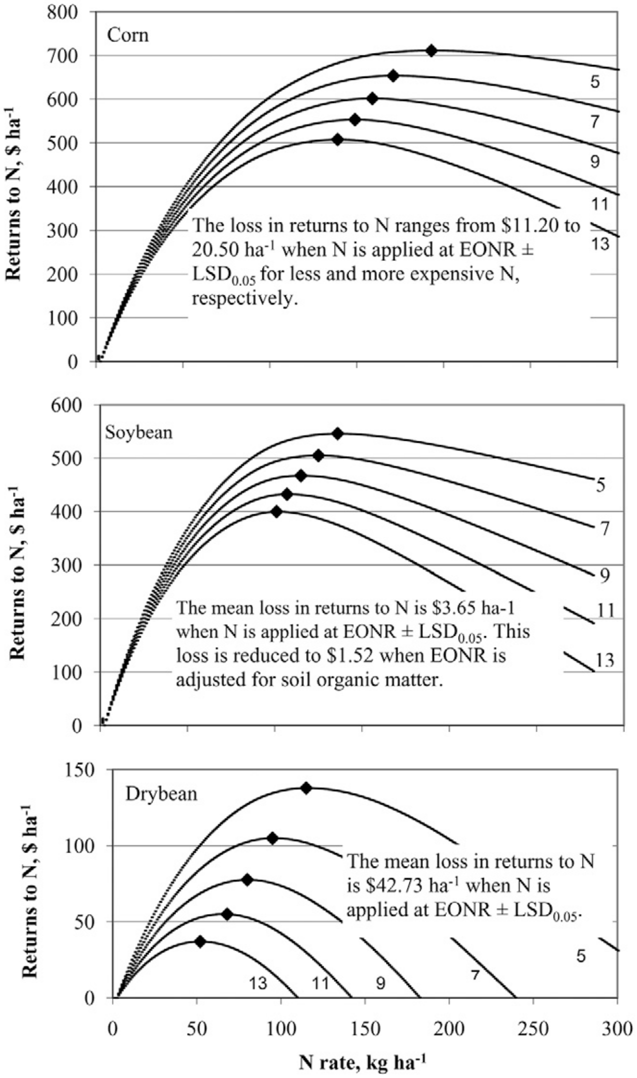

Fig. 4. The effect of N rate on gross returns to N applied to corn for five N/corn price ratios and where the cropping system was corn following (a) corn (*n* = 12), (b) soybean (*n* = 16), and (c) drybean (*n* = 4) as determined from 32 irrigated trials conducted in Nebraska in 2002–2004.

Table 4. The mean difference, and LSD 0.05, in grain yield and gross returns to applied nitrogen (RTN) for alternative means of predicting the economically optimum nitrogen rate (EONR) compared with measured EONR at five N/corn price ratios for irrigated corn in Nebraska.

Variable	Price of N relative to price of corn, (\$ kg^{-1}) (\$ kg^{-1})$^{-1}$				
	5	7	9	11	13
Cropping system = corn–corn: the mean UNL-N$_{2000}$ rate was 188 kg ha^{-1} with LSD 0.05 = 9.7.					
UNL-N$_{2000}$† – EONR rate, kg ha^{-1} N	8.6 ± 35.3	17.2 ± 32.2	27.8 ± 29.6	38.9 ± 27.2	46.8 ± 26.4
UNL-N$_{2000}$ adjustment factor	0.954	0.909	0.852	0.79	0.751
UNL-N$_{2000}$ – EONR yield, Mg ha^{-1}	–0.10 ± 0.18	–0.05 ± 0.16	0.02 ± 0.14	0.12 ± 0.11	0.20 ± 0.10
UNL-N$_{2000adj}$† – EONR yield, Mg ha^{-1}†	–0.14 ± 0.21	–0.13 ± 0.22	–0.13 ± 0.24	–0.15 ± 0.26	–0.14 ± 0.26
Mean EONR† – EONR yield, Mg ha^{-1}	–0.18 ± 0.26	–0.18 ± 0.27	–0.03 ± 0.47	–0.19 ± 0.31	–0.24 ± 0.31
UNL-N$_{2000}$ – EONR RTN, \$ ha^{-1}	–23.7 ± 7.7	–27.6 ± 13.6	–36.3 ± 22.6	–48.8 ± 31.6	–64.7 ± 40.6
UNL-N$_{2000adj}$ – EONR RTN, \$ ha^{-1}	–21.8 ± 10.3	–21.2 ± 10.6	–20.6 ± 14.1	–23.2 ± 17.2	–22.7 ± 20.9
Mean EONR – EONR RTN, \$ ha^{-1}	–28.2 ± 16.4	–28.4 ± 15.1	–5.6 ± 45.2	–29.6 ± 18.8	–39.0 ± 32.5
Cropping system = soybean–corn: the mean UNL-N$_{2000}$ rate was 122 kg ha^{-1} with LSD 0.05 = 16.1.					
UNL-N$_{2000}$ – EONR rate, kg ha^{-1} N	–6.3 ± 16.9	0.3 ± 16.1	7.6 ± 14.5	15.2 ± 13.1	20.5 ± 12.2
UNL-N$_{2000}$ adjustment factor†	1.052	0.998	0.938	0.875	0.832
UNL-N$_{2000}$ – EONR yield, Mg ha^{-1}	–0.17 ± 0.17	–0.14 ± 0.18	–0.07 ± 0.15	0.00 ± 0.14	0.07 ± 0.13
UNL-N$_{2000adj}$ – EONR yield, Mg ha^{-1}†	–0.36 ± 0.54	–0.10 ± 0.16	–0.08 ± 0.15	–0.06 ± 0.14	–0.05 ± 0.13
Mean EONR – EONR yield, Mg ha^{-1}	–0.07 ± 0.08	–0.07 ± 0.08	–0.07 ± 0.09	0.00 ± 0.16	–0.07 ± 0.13
EONR$_{SOM}$‡ – EONR yield, Mg ha^{-1}	–0.03 ± 0.03	–0.04 ± 0.05	–0.03 ± 0.06	–0.04 ± 0.07	–0.04 ± 0.08
UNL-N$_{2000}$ – EONR RTN, \$ ha^{-1}	–22.5 ± 20.5	–22.1 ± 20.1	–22.4 ± 18.8	–26.1 ± 19.9	–31.9 ± 21.9
UNL-N$_{2000adj}$ – EONR RTN, \$ ha^{-1}	–57.3 ± 84.6	–16.3 ± 13.5	–12.9 ± 10.3	–10.1 ± 9.4	–8.2 ± 8.5
Mean EONR – EONR RTN, \$ ha^{-1}	–11.0 ± 4.1	–12.0 ± 5.2	–11.0 ± 6.8	–0.2 ± 24.6	–10.4 ± 8.2
EONR$_{SOM}$ – EONR RTN, \$ ha^{-1}	–5.0 ± 16.8	–5.9 ± 21.7	–5.5 ± 25.3	–6.5 ± 28.5	–6.5 ± 31.8
Cropping system = dry bean–corn: the mean UNL-N$_{2000}$ rate was 161 kg ha^{-1} with LSD 0.05 = 42.2.					
UNL-N$_{2000}$ – EONR rate, kg ha^{-1} N	57.1 ± 45.5	68.1 ± 34.0	79.4 ± 30.3	85.8 ± 27.6	90.9 ± 26.3
UNL-N$_{2000}$ adjustment factor†	0.648	0.580	0.510	0.470	0.439
UNL-N$_{2000}$ – EONR yield, Mg ha^{-1}	0.10 ± 0.06	0.17 ± 0.16	0.24 ± 0.25	0.30 ± 0.21	0.35 ± 0.18
UNL-N$_{2000adj}$ – EONR yield, Mg ha^{-1}†	–0.07 ± 0.29	–0.07 ± 0.36	–0.08 ± 0.46	–0.08 ± 0.49	–0.09 ± 0.52
Mean EONR – EONR yield, Mg ha^{-1}	–0.11 ± 0.48	–0.12 ± 0.58	–0.13 ± 0.69	–0.13 ± 0.72	–0.13 ± 0.74
UNL-N$_{2000}$ – EONR RTN, \$ ha^{-1}	–30.0 ± 37.2	–49.9 ± 48.7	–75.1 ± 55.9	–103.1 ± 62.9	–133.4 ± 70.2
UNL-N$_{2000adj}$ – EONR RTN, \$ ha^{-1}	–11.2 ± 8.9	–11.7 ± 8.6	–13.1 ± 7.7	–13.7 ± 4.5	–14.1 ± 9.2
Mean EONR–EONR RTN, \$ ha^{-1}	–17.9 ± 30.1	–19.1 ± 26.2	–20.2 ± 22.3	–20.7 ± 16.5	–20.7 ± 17.1

† Three means of predicting EONR were compared, as well as a fourth for corn following soybean: the University of Nebraska corn N rate algorithm (UNL-N$_{2000}$, Ferguson et al., 2000); UNL-N$_{2000adj}$ determined by applying the UNL-N$_{2000}$ adjustment factor; mean EONR; and EONR$_{SOM}$ determined by adjusting mean EONR by soil organic matter level in the 0- to 20-cm depth with EONR$_{SOM}$ = mean EONR- (SOM – 2.66) × 18.

Recommendations for CD were considered to be similar to CC in UNL-N$_{2000}$ based on the understanding that little atmospheric N fixation commonly occurs with drybean. However, little immobilization of N and increased net mineralization is expected to occur with drybean crop residue, as occurs with soybean residue, compared with corn residue (Gentry et al., 2001). Nitrogen fixation by the previous grain legume crop apparently has little effect compared to net organic N mineralization on the crop's fertilizer replacement value (Bergerou et al., 2004). The UNL-N$_{2000}$ could be improved for CD by giving a previous crop N credit of 65 kg ha^{-1} when dry bean is the preceding crop, similar to the 50 kg ha^{-1} N credit currently given for CS.

Prediction of EONR was best for CC and CD using UNL-N$_{2000adj}$ and for CS using mean EONR adjusted for SOM (Table 4). Loss of RTN in prediction of EONR, compared with actual site-year EONR, can then be reduced to 22, 6, and 13 \$ ha^{-1} for CC, CS, and CD, respectively.

This research is especially applicable to high yield corn production with split N application in Nebraska. Expected corn yield varies widely by site-year in Nebraska when rainfed production is considered. Retaining EY as a factor in determining N rate is justified based on results for lower yield situations from earlier research. Therefore, the UNL-N$_{2000}$ adjusted by the factors that account for differences with mean EONR and for N/corn price ratio is likely to be the most accurate tool for estimating site-year EONR for rainfed conditions. The results are also only directly applicable when N is split-applied; we suggest that N rate be increased by 5 and 10% if more than 60% of the N is applied preplant in the spring and fall, respectively.

Modern, tactical N management concepts should involve a combination of anticipatory preplant and responsive in-season decisions. The N recommendation approaches assessed here are suitable for making general decisions on the average amount of N needed. Combining this with in-season application according to assessment of crop N and biomass status at one or more key growth stages is likely to provide another level of fine-tuning application rates and optimizing N use efficiency according to seasonal conditions and developing yield potential.

CONCLUSIONS

Corn yield with no N applied ranged from 5.6 to 12.7 Mg ha^{-1}, and was least and greatest for CC and CD, respectively. The mean response to applied N was for greatest for CC and least for CD. The EONR for irrigated corn was approximately 50 and 75 kg ha^{-1} less for CS and CD, respectively, compared with CC. Irrigated corn EONR was more variable for CC and CD compared with CS. The UNL-N_{2000} performed well at yields once adjusted for mean EONR and N/corn price ratio; it is expected to be the best option for extending the results to rainfed, lower yield situations. For irrigated CS, however, mean EONR adjusted for SOM predicted site-year EONR most accurately. The EONR for split application is likely to be less than for preplant spring and fall N applications, and N rates need to be adjusted accordingly, especially for field or management conditions with relatively high risk of N loss compared to the norm.

REFERENCES

Bergerou, J.A., L.E. Gentry, M.B. David, and F.E. Below. 2004. Role of N_2 fixation in the soybean N credit in maize production. Plant Soil 262:383–394.

Bundy, L.C., and E.S. Malone. 1988. Effect of residual profile nitrate on corn response to applied nitrogen. Soil Sci. Soc. Am. J. 85:1377–1383.

Dobermann, A., T. Arkebauer, K.G. Cassman, R.A. Drijber, J.L. Lindquist, J.E. Specht, D.T. Walters, H. Yang, D. Miller, D.L. Binder, G. Teichmeier, R.B. Ferguson, and C.S. Wortmann. 2003. Understanding corn yield potential in different environments. p. 67–82. *In* L.S. Murphy (ed.) Fluid focus: The third decade. Proc. 23rd Liquid Forum, Vol. 20. Fluid Fertilizer Foundation, Manhattan, KS.

Dobermann, A., and K.G. Cassman. 2002. Plant nutrient management for enhanced productivity in intensive grain production systems of the United States and Asia. Plant Soil 247:153–175.

Dobermann, A., and C.A. Shapiro. 2004. Setting a realistic corn yield goal. NebGuide G79-481-A. Available at http://ianrpubs.unl.edu/fieldcrops/g481.htm (verified 6 Oct. 2010). Coop. Ext., Inst. of Agric. and Natural Resources, Univ. of Nebraska–Lincoln.

Duvick, D.N. 2005. Genetic progress in yield of United States maize (*Zea mays* L.). Maydica 50:193–202.

Ferguson, R.B., G.W. Hergert, and E.J. Penas. 2000. Corn. p. 75–83. *In* R.B. Ferguson (ed.) Nutrient management for agronomic crops in Nebraska. Coop. Ext. EC 01-155-S. Univ. of Nebraska, Lincoln.

Ferguson, R.B., C.A. Shapiro, G.W. Hergert, W.L. Kranz, N.L. Klocke, and D.H. Krull. 1991. Nitrogen and irrigation management practices to minimize nitrate leaching from irrigated corn. J. Prod. Agric. 4:186–192.

Franzleubbers, A.J., C.A. Francis, and D.T. Walters. 1994. Nitrogen fertilizer response potential of corn and sorghum in continuous and rotated crop sequences. J. Prod. Agric. 7:277–284.

Gentry, L.E., F.E. Below, M.B. David, and J.A. Bergerou. 2001. Source of soybean N credit in maize production. Plant Soil 236:175–184.

Grassini, P., H. Yang, and K.G. Cassman. 2009. Limits to maize production in the Western Cornbelt: A simulation analysis for fully irrigated and rainfed conditions. Agric. For. Meteorol. 149:1254–1265.

Kyveryga, P.M., A.M. Blackmer, and T.F. Morris. 2007. Alternative benchmarks for economically optimal rates of nitrogen fertilization for corn. Agron. J. 99:1057–1065.

NCR-13. 1998. Recommended chemical soil test procedures for the North Central Region. North Central Regional Publ. 221. Missouri Agric. Exp. Stn., Columbia.

Oberle, S.L., and D.R. Keeney. 1990. Factors influencing corn fertilizer N requirements in the Northern U.S. Corn Belt. J. Prod. Agric. 3:527–534.

Ritchie, S.W., J.J. Hanway, and G.O. Benson. 1996. How a corn plant develops. SR-48. Iowa State Univ., Coop. Ext. Serv., Ames.

Sawyer, J.E., and E.D. Nafziger. 2005. Regional approach to making nitrogen fertilizer rate decisions for corn. p. 16–24. *In* Proc. of the 35th North-Central Extension Industry Soil Fertility Conf., Des Moines, IA. 16–17 Nov. 2005. Potash & Phosphate Inst., Brookings, SD.

Sawyer, J.E., and G.W. Randall. 2008. Nitrogen rates. p. 59–71. *In* J. Baker (ed.) URMSHNC (Upper Mississippi River Sub-basin Hypoxia Nutrient Committee). Final report: Hypoxia and local water quality concerns workshop. Am. Soc. Agric. biol. Eng., St. Joseph, MI.

Shapiro, C.A., R.B. Ferguson, G.W. Hergert, C.S. Wortmann, and D. Walters. 2009. Fertilizer suggestions for corn. EC 117. Univ. of Nebraska-Lincoln.

Schepers, J.S., and A.R. Mosier. 1991. Accounting for nitrogen in non-equilibrium soil–crop systems. p. 125–138. *In* R.F. Follett et al. (ed.) Managing nitrogen for groundwater quality and farm profitability. SSSA, Madison, WI.

Vanotti, M.B., and L.G. Bundy. 1994. Corn nitrogen recommendations based on yield response data. J. Prod. Agric. 7:249–256.

Varvel, G.E., and W.W. Wilhelm. 2003. Soybean nitrogen contribution to corn and sorghum in western Corn Belt rotations. Agron. J. 95:1220–1225.

Wortmann, C.S., A. Dobermann, R.B. Ferguson, G.W. Hergert, C.A. Shapiro, D.D. Tarkalson, and D.T. Walters. 2009. High yield corn response to applied phosphorus, potassium, and sulfur in Nebraska. Agron. J. 101:546–555.