Fertilizer Management

High-Yielding Corn Response to Applied Phosphorus, Potassium, and Sulfur in Nebraska

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ABSTRACT

Nutrient management recommendations may change as yield levels and efficiency of crop production increase. Recommendations for P, K, and S were evaluated using results from 34 irrigated corn (*Zea mays* L.) trials conducted in diverse situations across Nebraska. The mean yield was 14.7 Mg ha^{-1} with adequate fertilizer applied. The median harvest index values were 0.52, 0.89, 0.15, and 0.56 for biomass, P, K, and S, respectively. Median grain yields were 372, 49, and 613 kg kg^{-1} of aboveground plant uptake of P, K, and S, respectively. The estimated critical Bray-1 P level for corn response to 20 kg P ha^{-1} was 20 mg kg^{-1} when the previous crop was corn compared with 10 mg kg^{-1} when corn followed soybean [*Glycine max* (L.) Merr.]. Soil test K was generally high with only three site-years <125 mg kg^{-1}. Over all trials, application of 40 kg K ha^{-1} resulted in a 0.2 Mg ha^{-1} mean grain yield decrease. Application of 22 kg S ha^{-1} did not result in significant yield increase in any trial. Soil test results accounted for twice as much variation in nutrient uptake when soil organic matter (SOM) and pH were considered in addition to the soil test nutrient values. The results indicate a need to revise the current recommendation for P, to maintain the current K and S recommendations, and to use SOM and pH in addition to soil test nutrient values in estimating applied nutrient requirements for irrigated high yield corn production.

On-going improvement of nutrient recommendations for crops is necessary because of changes in yield levels, varieties and production practices, and economic conditions. In the western Corn Belt and Great Plains of the United States, many land-grant universities including the University of Nebraska–Lincoln (UN-L) have utilized the deficiency correction approach to making nutrient recommendations. Soil tests are used with other production information to recommend nutrient application based on the probability of economic response.

The basis for calibration of the Bray-1 P and Olsen P soil tests was published by Olson et al. (1954), with further refinement of the interpretation of soil test results using later research results including different rates for broadcast and band application (Shapiro et al., 2003). Current UN-L recommendations do not recommend P and K application for corn when Bray-1 P is greater than 15 mg kg^{-1} and exchangeable K is greater than 124 mg kg^{-1}, respectively. Recommended S application is limited to sandy soils with less than 10 mg kg^{-1} SOM and <8 mg kg^{-1} SO_4–S by $Ca(H_2PO_4)_2$ extraction.

In studies conducted more than 20 yr ago, the UN-L recommendations for corn were found to be more profitable with less P, K, and S applied compared with recommendations based on nutrient replenishment or other approaches (Olson et al., 1982, 1987; McCallister et al., 1987). These results verified the UN-L P recommendations and there were no yield responses to applied K.

Soil test calibration may be needed for high yield situations and current cropping and tillage systems. Current P and K recommendations were mainly based on research conducted when mean corn grain yields in Nebraska were less than 5 Mg ha^{-1} compared with the 2008 average of more than 10 Mg ha^{-1} (USDA-NASS, 2008) and with yields often exceeding 15 Mg ha^{-1}. More recent research conducted in Iowa supports the current UN-L recommendations, although P application when Bray-1 P is between 15 and 20 mg kg^{-1} could be economical when the P fertilizer/corn price ratio is relatively low (Mallarino and Blackmer, 1992; Webb et al., 1992). Results from 26 no-till trials conducted in Iowa support the UN-L P recommendation for corn; yield of corn following soybean in rotation was increased by P application in starter fertilizer for 8 of 11 cases where Bray-1 P was less than 12 mg kg^{-1}, but in no cases where Bray-1 P was greater than 12 mg kg^{-1} (Bordoli and Mallarino, 1998). Corn yields ranged from 5.4 to 12.9 Mg ha^{-1}. In another study in Iowa, however, critical Bray-1 P levels were determined to be between 15 and 21 mg kg^{-1} for corn (Dodd and Mallarino, 2005). The response was similar for 14 kg P ha^{-1} as for higher rates. Research has been conducted in Nebraska on P placement (Sleight et al., 1984; Raun et al., 1987; Rehm et al., 1988; Eghball and Sander, 1989a, 1989b; Eghball et al., 1990) that led to differing rates with broadcast compared with band application.

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Abbreviations: GY, grain yield; HI, harvest index; IE, internal efficiency or grain produced per unit of nutrient in aboveground biomass; RIE, reciprocal of IE, or nutrient uptake require per unit of grain; SOM, soil organic matter; UN-L, University of Nebraska–Lincoln; UP, total phosphorus uptake in the aboveground biomass; UK, total potassium uptake in the aboveground biomass; US, total sulfur uptake in the aboveground biomass.

Illite is a major K source in Nebraska soils, including coarse-textured soils (Fawzi and Drew, 1966). Significant yield responses to applied K did not occur on sandy soils in northeastern Nebraska where exchangeable K was below the critical level of 125 mg kg (Rehm et al., 1981, 1983; Rehm and Sorensen, 1985). On irrigated and nonirrigated Mollisol soils testing high in K, there was often a yield depression at the highest K rate (McCallister et al., 1987). The current UN-L recommendation is supported by the findings of Mallarino and Blackmer (1994), who determined the critical soil K value for profit maximization to be 112 mg kg^{-1} by ammonium acetate extraction or 70 mg kg^{-1} by Mehlich III extraction. They estimated the rate of K release at these soil test K levels to be 1.0 kg ha^{-1} d^{-1}.

Fertilizer S recommendations for Nebraska soils were based on research by Rehm (1978, 1984, 1993), and consider primarily soil texture and SOM (Rehm, 2000). Calcium-phosphate extracted S (Fox et al., 1964) was considered in sandy soils with low SOM in the current UN-L recommendation. There was no corn grain yield response to S in starter fertilizer in 12 trials conducted on medium and fine-texture soil in eastern Nebraska (Wortmann et al., 2006a).

Olson et al. (1958) found a close correlation between soil test P and K in the 0- to 20-cm and 20 to 50-cm soil depths and soil tests were calibrated for the 0- to 20-cm depth. More than 40 additional years of intensive crop production may have affected nutrient distribution in the soil profile and may imply a need for differing soil sampling procedures. Nutrient stratification develops with no-till, especially for P (Garcia et al., 2007), but recommendations based on sampling the 0- to 20-cm depth may still be most appropriate for no-till and tilled fields (Mallarino and Borges, 2006).

Interpretation of soil test results for estimation of soil capacity to supply nutrients to a crop might be improved by considering soil pH and SOM together with soil nutrient level (Janssen et al., 1990). The capacity of soil, together with decomposing plant residues, to supply nutrients is equal to or greater than crop nutrient uptake with no nutrients applied and the capacity of nutrient supply can be related to estimated crop nutrient uptake to achieve expected yields. Grain yield per unit of nutrient uptake, or the internal efficiency of nutrient use (IE) (Witt et al., 1999), may vary with level of nutrient availability, production systems, hybrids, and various other abiotic and biotic factors. Therefore, IE can range from maximum nutrient accumulation to maximum nutrient dilution for yield per unit of nutrient uptake.

The objectives of this research were to: (i) compare soil test P sampling and analytical procedures; (ii) improve estimation of soil nutrient supply capacity and crop nutrient uptake; and (iii) verify or fine-tune fertilizer P, K, and S recommendations for high yield corn production across the major corn production agroecological zones and crop rotations.

MATERIALS AND METHODS

Nutrient response trials were conducted from 2002 to 2004 for 34 site-years with 11 to 12 trials conducted each year across Nebraska, including most major irrigated corn areas (Table 1). Of the 34 site-years, 13 and 21 were on research stations and producers' fields, respectively. Nine, 11, and 14 trials were conducted with ridge-till, no-till, and conventional tillage consisting of disk or chisel plow tillage, respectively. Corn followed corn, soybean, and dry bean (*Phaseolus vulgaris* L.) in 16, 13, and 5 site-years, respectively, with the dry bean production in western Nebraska. The elevation range was from 370 to 1190 m above sea level and the latitude from approximately 40.1 to 42.4° N. Soil properties ranged widely as addressed below and in Table 1. Only the Paxton 2002 and 2003 trials were repeated on the same field site. Therefore, the results are widely applicable to high yield corn production in temperate areas of similar daylength.

Eleven site-years had either loamy sand or sandy loam soil and the remaining had either silt loam or silty clay loam soil (Table 1). Soil samples of the 0- to 20-cm depth were analyzed according to the Missouri Agricultural Experiment Station (1998). Soil organic matter ranged from 7 to 34 mg kg^{-1} with a median of 25.5 mg kg^{-1}. Initial soil fertility characteristics varied widely among the sites. About 40% of the sites had soil test P levels below the current critical level of 15 mg kg^{-1} Bray-1 P, but soil test K was below the current critical level of 125 mg kg^{-1} at just two sites. None of the sites were below the critical level in both P and K.

The treatment combinations included P applied at 0, 20, and 40 kg ha^{-1} and K applied at 0, 40, and 80 kg ha^{-1} (Table 1). In addition, one or two S-applied treatments were included in five site-years with medium or fine-texture soil and four site-years with sandy soil at rates of 0 and 20 kg ha^{-1}. All trials also included treatments for evaluation of crop response to four N rates but these results are not addressed in this article. The N rates were constant within trials for testing the effects of P, K, and S rates. Fertilizer P and K were broadcast-applied at or shortly before planting as triple super phosphate and potassium chloride, respectively, and incorporated at the conventional tillage sites. Sulfur was broadcast-applied as gypsum.

The experimental design was a randomized complete block with four replications. The minimum plot size was six rows (0.76 m row^{-1}) by 15 m, but plot width was often wider depending on planting equipment.

The cooperating farmer chose the hybrid and weed control practices. Nitrogen was applied in split applications of 60% preplant and 40% at the V6 stage for medium or fine-texture soils, and 40% preplant and 30% each at the V6 and V10 stages for sandy soils (Table 1). Sulfur was applied to all plots for a few trials with sandy soil. Soil tests did not indicate a need for Zn and other nutrients and these were not applied. The targeted plant density was 7.4 to 8.6 plants m^{-2}. Irrigation was applied to maintain available soil water above 50% of field capacity at all growth stages to avoid any interference of water deficits with nutrient response. Sites had either center-pivot or furrow irrigation.

Soil Sampling and Measurements

Soil samples collected for each plot before planting with hand probes were comprised of 10 cores each from the 0- to 20-cm and the 20- to 40-cm depths, each centered between crop rows except in ridge-till sites where the soil cores were collected on the ridge shoulder, about 15 cm from the row. At no-till sites, the first core was split for the 0- to 10-cm and the 10-cm to 20-cm depths. The samples were analyzed for texture

Table 1. Site-year characteristics, including means and standard deviations for soil test properties, for 34 irrigated corn N response trials conducted in Nebraska.

	Site-year	Soil†	Texture	Previous crop	Till‡	SOM	Soil pH	Bray-1 P	Olsen P	Soil K	N rate§			
											P0-20	P20-40	K0-40	K40-48
						mg g–1		mg kg–1			kg ha^{-1}			
							2002							
1.	Mead	Tomek	siCL	soybean	NT	31, 1.6	6.2, 0.20	13, 5.2	8.2, 3.7	471, 51	140	280	140	280
2.	Wymore¶	Wymore	siCL	soybean	NT	27, 1.4	6.3, 0.14	5, 0.5	2.8, 0.7	376, 18	140	280	140	280
3.	Brunswick¶	Thurman	lS	soybean	NT	7, 1.3	6.5, 0.14	21, 4.2	14.3, 3.0	93, 16	140	280	140	280
4.	Concord¶	Nora	siL	soybean	NT	33, 2.0	5.8, 0.12	11, 3.0	8.0, 2.2	292, 73	140	280	140	280
5.	Bellwood¶	Muir	lS	corn	RT	14, 2.1	6.3, 0.30	15, 3.6	10.0, 3.1	106, 21	181	321	181	321
6.	Cairo	Hall	siL	corn	RT	25, 2.0	7.1, 0.24	13, 6.4	10.7, 4.8	530, 72	190	336	190	336
7.	Clay Center	Hastings	siL	corn	RT	29, 2.1	6.9, 0.10	17, 10.5	16.4, 10.3	516, 84	190	336	190	336
8.	SCAL	Crete	siL	soybean	CT	30, 1.6	6.1, 0.24	13, 2.4	9.1, 2.8	517, 69	140	280	140	280
9.	North Platte	Cozad	siL	corn	RT	21, 1.5	7.2, 0.16	10, 1.6	4.6, 1.1	505, 64	190	336	190	336
10.	Paxton¶	Vetal	lS	corn	CT	14, 1.4	6.3, 0.27	17, 4.6	11.2, 3.7	407, 123	190	336	190	336
11.	Scottsbluff	Mitchell	siL	drybean	CT	20, 1.7	8.0, 0.07	46, 8.3	26.5, 5.0	604, 53	190	336	190	336
12.	Box Butte	Creighton	sL	drybean	CT	18, 1.6	7.0, 0.24	74, 7.4	40.0, 7.4	644, 60	190	336	190	336
							2003							
13.	Mead	Tomek	siL	soybean	NT	30, 1.5	6.4, 0.19	10, 2.9	5.9, 2.2	362, 41	168	280	168	280
14.	Pickrell	Wymore	siCL	soybean	NT	29, 1.9	5.8, 0.13	11, 3.0	7.4, 2.4	406, 52	168	280	168	280
15.	Brunswick¶	Crofton	siL	soybean	NT	19, 2,1	6.8, 0.25	19, 5.7	12.2, 3.6	329, 38	168	280	168	280
16.	Concord¶	Nora	siL	soybean	NT	30, 1.9	5.8, 0.28	37, 11.3	20.9, 5.7	502, 68	168	280	168	280
17.	Bellwood¶	Muir	sL	corn	RT	13, 1.6	6.0, 0.42	38, 10.7	21.1, 7.1	147, 32	224	375	224	375
18.	Cairo	Hall	siL	corn	RT	27, 2.3	6.9, 0.41	16, 7.5	11.8, 5.3	624, 61	224	336	224	336
19.	SCAL	Crete	siL	soybean	CT	33, 2.8	6.6, 0.13	23, 14.2	13.9, 9.6	608, 85	168	280	168	280
20.	North Platte	Cozad	siL	corn	RT	20, 2.1	7.3, 0.11	12, 2.6	5.8, 1.2	554, 59	224	336	224	336
21.	Paxton¶	Vetal	lS	corn	CT	13, 1.5	6.3, 0.24	19, 6.0	8.6, 4.0	450, 47	224	336	224	336
22.	Scottsbluff	Mitchell	siL	drybean	CT	16, 2.6	7.5, 0.15	40, 10.5	25.8, 8.7	474, 59	224	336	224	336
23.	Box Butte	Creighton	sL	drybean	CT	17, 1.1	7.3, 0.21	22, 7.7	11.0, 4.1	491, 39	224	336	224	336
							2004							
24.	Mead	Tomek	siCL	soybean	NT	34, 2.2	6.3, 0.18	7, 2.2	4.9, 1.6	322, 45	168	280	168	280
25.	Pickrell	Wymore	siCL	soybean	NT	28, 2.5	6.2, 0.19	6, 2.8	3.8, 1.9	396, 59	168	280	168	280
26.	Brunswick¶	Thurman	lS	soybean	CT	9, 2.4	6.3, 0.33	21, 9.5	11.1, 6.2	91, 35	168	280	168	280
27.	Concord¶	Kennebec	siL	soybean	NT	28, 2.7	6.4, 0.16	28, 6.5	19.8, 4.4	479, 70	168	280	168	280
28.	North Bend	Moody	siCL	soybean	CT	30, 2.3	6.4, 0.14	13, 8.2	8.6, 6.1	458, 69	168	280	168	280
29.	Cairo	Hord	siL	corn	RT	24, 2.0	6.7, 1.9	22, 5.4	12.1, 3.8	387, 63	224	336	224	336
30.	Funk	Holdrege	siL	corn	RT	28, 2.1	6.8, 0.25	11, 11.4	6.5, 7.8	529, 57	224	336	224	336
31.	SCAL	Butler	siL	soybean	CT	26, 2.1	6.9, 0.17	28, 9.3	20.3, 6.4	492, 42	168	280	168	280
32.	Brosius	Hord	sL	corn	CT	10, 2.8	4.8, 0.11	88, 22.6	45.8, 12.1	202, 33	224	336	224	336
33.	Spurgin	Vetal	lS	corn	CT	20, 4.3	6.3, 0.25	26, 6.9	14.2, 4.2	426, 86	224	336	224	336
34.	Box Butte	Creighton	sL	drybean	CT	27, 3.5	7.1, 0.18	52, 8.2	34.5, 7.4	706, 69	224	336	224	336

† Soil series names: Butler, fine, smectitic, mesic Vertic Argiaquolls; Cozad, coarse-silty, mixed, superactive, mesic Typic Haplustolls; Creighton, coarse-loamy, mixed, superactive, mesic Aridic Haplustolls; Crete, fine, smectitic, mesic Pachic Argiustolls; Crofton, fine-silty, mixed, superactive, calcareous, mesic Udic Ustorthents; Hall, fine-silty, mixed, superactive, mesic Pachic Argiustolls; Hastings, fine, smectitic, mesic Udic Argiustolls; Hord, fine-silty, mixed, superactive, mesic Cumulic Haplustolls; Holdrege, fine-silty, mixed, superactive, mesic Typic Argiustolls; Kennebec, fine-silty, mixed, superactive, mesic Cumulic Hapludolls; Mitchell, coarse-silty, mixed, superactive, calcareous, mesic Ustic Torriorthents; Moody, fine-silty, mixed, superactive, mesic Udic Haplustolls; Muir, fine-silty, mixed, superactive, mesic Cumulic Haplustolls; Nora, fine-silty, mixed, superactive, mesic Udic Haplustolls; Thurman, sandy, mixed, mesic Udorthentic Haplustolls; Tomek, fine, smectitic, mesic Pachic Argiudolls; Wymore, fine, smectitic, mesic Aquertic Argiudolls; Vetal, coarse-loamy, mixed, superactive, mesic Pachic Haplustolls.

‡ Till = tillage system including conventional tillage consisting of disk or chisel plow tillage (CT), no-till (NT), and ridge till (RT). SOM = soil organic matter. Soil texture classes included silty clay loam (siCL), loamy sand (lS), silt loam (siL), and sandy loam (saL).

§ The N rates for P and K treatments varied by site-year and, in some cases, by rate comparison. P0-20 = the comparison of the 0 and 20 kg P ha^{-1} rates; P20-40, K0-40, and K40-80 have similar meanings. The P0-20 and P20-40 comparisons were with 40 kg K ha^{-1} applied. The K0-40 and K40-80 comparisons were with 20 kg P ha^{-1} applied.

¶ Site-years with treatment for applied sulfur effects. The N rate was consistent for the 0 and 22 kg S ha^{-1} rate comparisons within each site year but varied across site-years, ≥140 kg ha^{-1} for CS and ≥252 kg ha^{-1} for CC and CDB. The P and K rates for S comparison treatments were 20 and 40 kg ha^{-1}, respectively.

class, SOM, ammonium acetate–exchangeable K, pH, buffer pH, Bray-1 P, Olsen P, and Ca-phosphate–extracted S (Missouri Agricultural Experiment Station, 1998).

A six-plant sample was collected at physiological maturity to determine P, K, and S concentrations in grain and stover, and to calculate P, K, and S harvest index (HI) and uptake. Grain yield and final plant density were determined from two 6.1-m row segments. Final plot dry matter yield was estimated from the grain yield measured at harvest and the HI value. Grain and aboveground biomass yield, final plant density, and P, K, and S uptake in grain and stover were determined.

Statistical Analysis

Statistical analyses were conducted using Statistix 9 (Analytical Software, Tallahassee FL). Reported treatment effects and equations were significant when $P < 0.05$. Analyses of variance (ANOVA) were conducted for individual site-years using the nine treatments that were consistent across all research sites. The effects of applied P and K were determined with linear one-degree-of-freedom contrasts. When it was apparent that the critical soil test P level for response to applied P differed according to previous crop, combined ANOVA were conducted for the effect of applied P with sets of site-years. These sets were determined in consideration of individual site-year results and

Table 2. Descriptive statistics for yield, yield components, nutrient uptake, and nutrient use efficiency values for data collected from 34 high yield corn trials conducted in Nebraska (n = 1483 observations). Grain yield is expressed for 155 g kg^{-1} water content whereas other yield and weight variables are on an oven-dry basis.

Parameter†	Mean	SD	Max.	Min.	Median	Lower 25%	Upper 25%
Grain, Mg ha^{-1}	13.86	2.26	19.01	3.66	14.21	12.57	15.51
Stover, Mg ha^{-1}	10.14	2.81	10.14	3.56	9.78	8.07	11.79
Cobs, Mg ha^{-1}	1.53	0.33	1.53	0.48	1.47	1.32	1.67
Biomass, Mg ha^{-1}	23.74	4.10	35.07	8.38	23.89	20.92	26.57
100-grain wt., g	31.3	3.9	42.7	21.3	31.0	28.7	34.3
Ears m^{-2}	7.28	0.89	12.30	3.99	7.34	6.80	7.66
Kernels m^{-2}	3867	564	5939	1375	3872	3556	4225
Kernels ear^{-1}	536	87	921	210	528	485	582
Grain P, g kg^{-1}	2.69	0.80	5.15	0.77	2.66	2.16	3.23
Grain P, kg ha^{-1}	32.8	12.0	70.8	6.8	31.3	23.6	41.2
Grain K, g kg^{-1}	3.63	0.64	5.63	1.60	3.65	3.21	4.09
Grain K, kg ha^{-1}	44.0	11.4	76.3	11.8	43.8	35.6	51.9
Grain S, g kg^{-1}	1.03	0.14	1.37	0.09	1.03	0.93	1.13
Grain S, kg ha^{-1}	12.5	2.9	20.2	1.0	12.5	10.6	14.6
Stover P, g kg^{-1}	0.44	0.36	2.89	0.05	0.33	0.20	0.53
Stover P, kg ha^{-1}	37.6	13.0	79.9	10.8	35.8	27.9	46.3
Stover K, g kg^{-1}	23.82	4.50	40.08	12.04	23.74	20.74	26.82
Stover K, kg ha^{-1}	300.8	96.3	591.6	88.1	289.2	229.0	370.4
Stover S, g kg^{-1}	0.92	0.22	1.76	0.39	0.90	0.77	1.05
Stover S, kg ha^{-1}	22.4	5.1	41.2	6.2	22.3	18.9	25.9
HI, g kg^{-1}, kg kg^{-1}	0.51	0.06	0.62	0.34	0.52	0.47	0.56
P HI, kg kg^{-1}	0.87	0.08	0.98	0.47	0.89	0.83	0.92
K HI, kg kg^{-1}	0.15	0.04	0.30	0.06	0.15	0.12	0.18
S HI, kg kg^{-1}	0.56	0.07	0.79	0.08	0.56	0.51	0.61
P IE, P_0‡, n = 50, kg kg^{-1}	452	102	681	244	438	385	495
P IE, n = 1433, kg kg^{-1}	405	137	1105	184	372	303	469
P RIE, P_0, n = 50, kg Mg^{-1}	2.32	0.53	4.09	1.47	2.28	2.02	2.59
P RIE, n = 1433, kg Mg^{-1}	2.72	0.81	5.45	0.90	2.69	2.13	3.29
K IE, kg kg^{-1}	49.7	13.7	98.0	21.5	48.8	38.2	58.6
K RIE, kg Mg^{-1}	21.7	6.1	46.5	10.2	20.5	17.1	26.2
S IE, kg kg^{-1}	636	115	1073	314	613	553	697
S RIE, kg Mg^{-1}	1.60	0.29	3.19	0.97	1.63	1.38	1.81

† HI, harvest index; IE, internal efficiency of P use expressed as grain produced per unit of aboveground plant nutrient uptake at physiological maturity; RIE, reciprocal internal efficiency expressed as amount of plant nutrient uptake per unit of grain produced.

‡ P_0 = determined for the no P applied treatment for corn following corn trials with Bray-1 P < 20 mg kg^{-1} and for corn following soybean trials with Bray-1 P <10 mg kg^{-1}.

included: soybean as the previous crop and Bray-1 P < 10, >10, and >20 mg kg^{-1}; corn as the previous crop with Bray-1 P < 20 and >20 mg kg^{-1}; and drybean as the previous crop with Bray-1 P > 20 mg kg^{-1}. Combined ANOVAs were conducted for applied K effects by previous crop. Combined ANOVAs were conducted by soil texture group for applied S effects using only those treatments necessary for testing the effect of S.

Regression analyses were used to relate Bray-1 P to Olsen P and to determine soil depth effects on Bray-1 P and soil test K. Regression analyses were also used to estimate soil nutrient supply from soil test results and to determine the relationship of nutrient uptake with yield. Internal efficiency of nutrient use, or grain utilization efficiency as grain dry weight per unit of nutrient uptake, was determined for P, K, and S (Witt et al., 1999). Reciprocal IE (RIE), or the amount of nutrient needed to produce 1 Mg of grain, was calculated. Grain yield was related to nutrient uptake using nonlinear regression analysis.

RESULTS AND DISCUSSION

Bray-1 P and soil test K at 0- to 20-cm soil depth ranged from 5 to 84 and 93 to 696 mg kg^{-1}, respectively (Table 1). The descriptive statistics for yield, yield components, nutrient uptake, and nutrient use efficiency for P, K and S were summarized in Table 2.

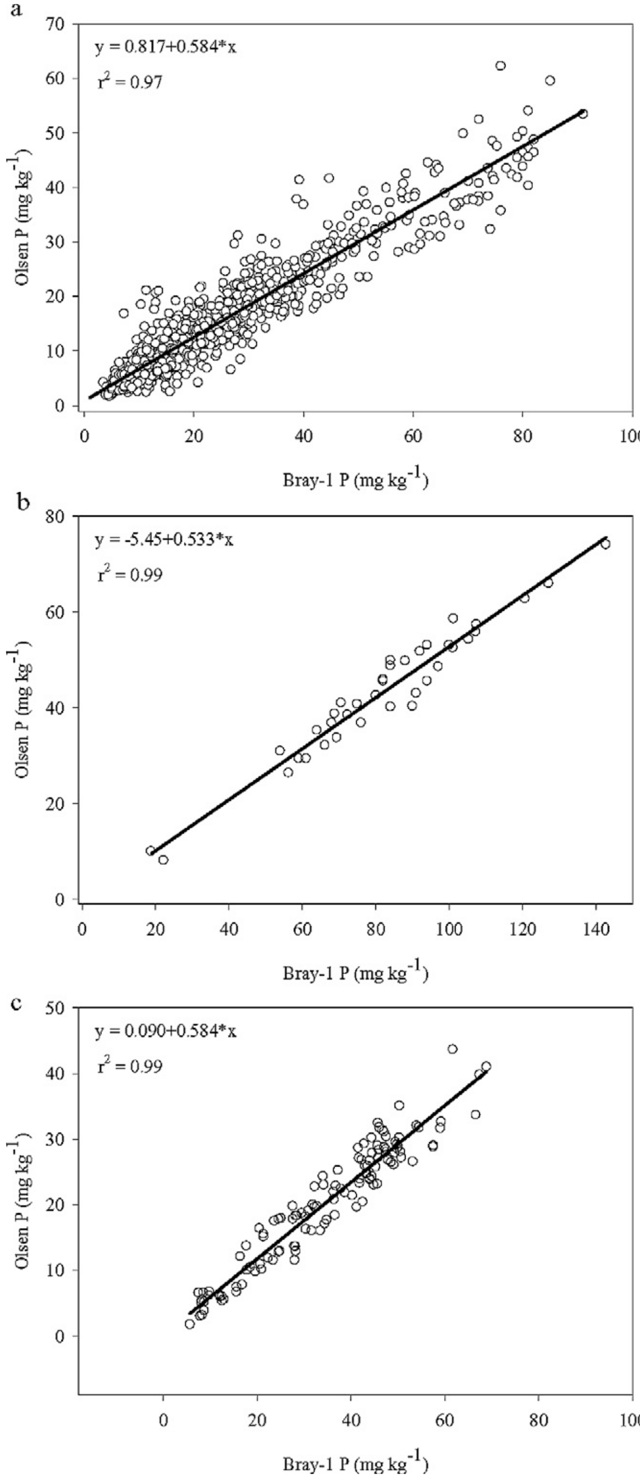

Fig. 1. Relationship between Bray-1 P and Olsen P at a sample depth of 0- to 20-cm for a soil pH of (a) 5.0 to 7.4 (n = 1299), (b) <5.0 (n = 37), and (c) >7.4 (n = 122) for soil samples collected from 34 site-years in Nebraska.

Soil Test P

Bray-1 P and Olsen P were highly correlated (r^2 = 0.97) over the whole range of soil test P levels, including for the acid and alkaline soil samples (Fig. 1a). However, the r^2 was only 0.67 when the range of data was limited to Bray-1 P < 25 mg kg^{-1},

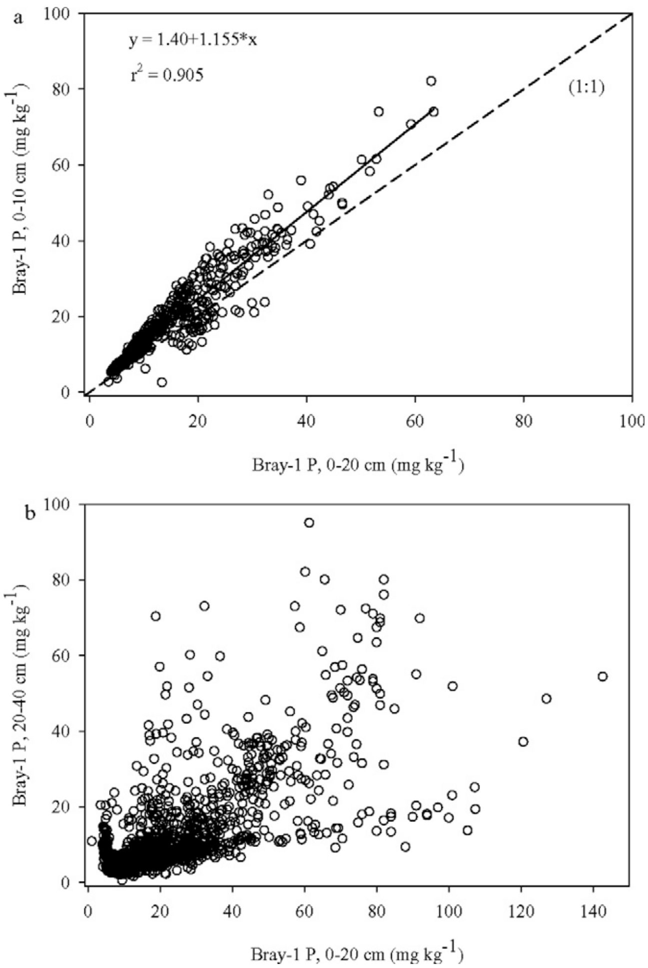

Fig. 2. The relationship of Bray-1 P at 0- to 20-cm with (a) 0- to 10-cm depth for soil samples collected from 11 no-till site-years (n = 508), and (b) 20- to 40-cm depths for soil samples collected from 34 site-years (n = 1458) in Nebraska.

the important range for agronomic soil P testing (Olsen P = 0.577 + 0.592 Bray-1 P). Currently, the UN-L interpretation of soil test P results uses an Olsen to Bray-1 P ratio of 0.67 (Shapiro et al., 2003). With this data set, the ratio was 0.67 when Bray-1 P was 10 mg kg^{-1}, but the ratio increased and decreased as Bray-1 P decreased or increased from 10 mg kg^{-1}, respectively. When soil pH < 5, the ratio increased as soil test P increased as a result of the negative y intercept (Fig. 1b). For alkaline soils, the ratio of Olsen to Bray-1 P is 0.59 over a wide range of soil test P levels (Fig. 1c). When using the complete data set to relate Olsen to Bray-1 P, the y intercept and the slope were both greater than found by Mallarino and Blackmer (1992).

Bray-1 P values for the 0- to 10-cm depth were higher but closely related to the values for the 0- to 20-cm depth at the no-till site-years (Fig. 2a). Development of P stratification under no-till conditions is common (Garcia et al., 2007). Bray-1 P values for the 20- to 40-cm depth were not related to the values for the 0- to 20-cm depth (Fig. 2b), differing with the findings of Olson et al. (1958) possibly due to an additional 50 yr of extraction and P application to surface soil.

Soil test P in the 0- to 20-cm depth was weakly related to plant P uptake (UP) when no P was applied, but the predictability of UP improved by including SOM and pH in the model. For corn after corn (n = 47), with site-year 32 excluded because of very high soil test P and low pH, the following was determined:

$$UP = 29.04 + 0.314 \text{ Bray-1 P}, R^2 = 0.16$$

$$UP = 27.19 + 0.710 \text{ Olsen P}, R^2 = 0.30$$

$$UP = 18.46 + 4.17 \text{ SOM} + 0.0635 \text{ Bray-1 P pH}, R^2 = 0.34$$

For corn following soybean (n = 61), soil test P was related to UP as follows:

$$UP = 16.9 + 1.56 \text{ Bray-1 P}, R^2 = 0.29$$

$$UP = 19.9 + 2.01 \text{ Olsen P}, R^2 = 0.27$$

$$UP = -100.2 + 1.96 \text{ Bray-1 P} - 0.020 \text{ Bray-1 P}^2 + 0.745 \text{ SOM} + 15.21 \text{ pH}, R^2 = 0.61$$

$$UP = -38.5 + 1.34 \text{ Olsen P} + 10.06 \text{ pH}, R^2 = 0.49$$

Soil test P at 0- to 10-cm and 20- to 40-cm depths were not significant in these equations. The results generally agree with Janssen et al. (1990), who found that including soil organic C and pH with soil test P improved the estimation of soil P supply.

There was a trend for soil test P to be lower and higher where the preceding crop was soybean and dry bean, respectively, compared with corn (Fig. 3). Soil test P also tended to be less with no-till and more with conventional tillage compared with ridge-till site-years. This was confounded, however, with previous crops as all ridge-till site-years were corn following corn, all corn following dry bean were conventionally tilled, and most of the corn following soybean site-years were no-till fields.

Response to Applied Phosphorus

The application of 20 kg ha^{-1} P resulted in grain yield increases for four site-years, decreases for two site-years, and no significant effect for other site-years (Table 3). Aboveground biomass yield was affected in five site-years with only two site-years having increased biomass yield with P application. The mean P effect on grain and biomass yield over all site-years was not significant. Grain P was increased in four site-years and plant P uptake was increased in five site-years and the overall means were increased with P application. Phosphorus HI was increased and decreased in two and three site-years, respectively, and the overall mean P HI was reduced with P application.

The mean response of grain and biomass yield and plant and grain P uptake to application of 20 kg ha^{-1} P was much greater when the previous crop was corn compared with soybean for Bray-1 P < 20 mg kg^{-1} and Olsen P < 12 mg kg^{-1} (Table 3; Fig. 3). For corn following soybean, response of these traits to applied P was significant only for Bray-1 P < 10 mg kg^{-1} and

Olsen P < 7 mg kg^{-1}. Mean P uptake was greater when the previous crop was soybean compared with corn for Bray-1 P < 20 but this was because of unusually high P uptake at Brunswick in 2003. When this site-year was excluded, mean plant uptake was 33.0 and 35.1 and grain P uptake was 29.4 and 31.2 kg ha^{-1}, respectively, for corn following soybean with 0 and 20 kg ha^{-1} P applied. Phosphorus HI was affected by P application only with corn following soybean when Bray-1 P was >20 mg kg^{-1}. Application of 20 kg ha^{-1} P had no effect on crop performance for Bray-1 P > 20 mg kg^{-1}. Application of an additional 20 kg ha^{-1} P did not result in significant yield increases. Yield response to applied P was associated with increased number of kernels ear^{-1} and m^{-2} for corn following corn, and with increased ear m^{-2} and kernel m^{-2} for corn following soybean (Table 4). Other yield components were not affected by P application.

Internal P-use efficiency ranged from 1100 to 200 kg grain kg^{-1} UP when plant P was extremely diluted or concentrated, respectively, with a median of 372 kg kg^{-1} (Table 2). Mean crop P requirement can be estimated for expected grain yield (GY) according to the following quadratic regression equations:

$$\text{UP (for all cropping systems)} = 35.5 - 3.28\ \text{GY} + 0.241\ \text{GY}^2,\ R^2 = 0.28,\ n = 1484$$

$$\text{UP (for corn following corn)} = 33.8 - 2.97\ \text{GY} + 0.220\ \text{GY}^2,\ R^2 = 0.50,\ n = 583$$

$$\text{UP (for corn following soybean)} = 13.48 + 0.143\ \text{GY}^2,\ R^2 = 0.32,\ n = 700$$

The soil test equations for predicting UP did not improve predictiveness of response compared with using soil test P thresholds. For corn following corn, the mean grain yield response to applied P was 0.70 Mg ha^{-1} for Bray-1 P < 20 mg kg^{-1} compared with 0.67 Mg ha^{-1} for the best selection of sites with the complex soil test equation. The threshold for response was 37 kg ha^{-1} of UP. For corn following soybean, the mean grain yield response to applied P was 0.84 Mg ha^{-1} for Bray-1 P < 10 mg kg^{-1} compared with 0.49 Mg ha^{-1} for the best selection

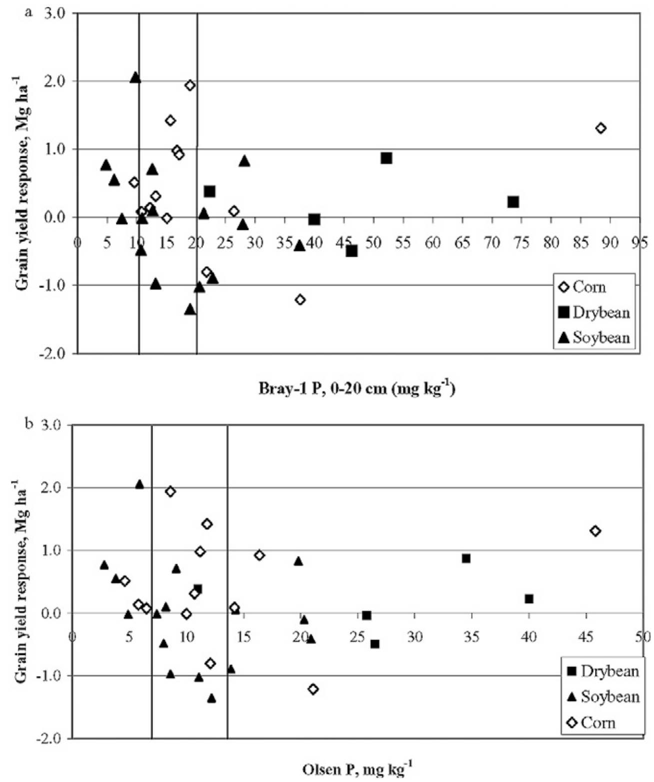

Fig. 3. Corn grain yield response to 20 kg ha^{-1} P, relative to (a) Bray-1 and (b) Olsen soil test P with corn, dry bean, or soybean as the preceding crop. Mean response of corn following soybean was significant when Bray-1 and Olsen P were less than 10 and 7 mg kg^{-1}, respectively. Mean response of corn following corn was significant when Bray-1 and Olsen P were less than 20 and 13.5 mg kg^{-1}, respectively.

Table 3. The effect of 20 compared with 0 kg ha^{-1} P applied to corn in 34 trials conducted in Nebraska on yield, P uptake, and P HI. Grain yield is expressed for 155 g kg^{-1} water content while biomass yield, HI and P uptake are on an oven-dry basis.

	P rate, kg ha^{-1}									
	0	20	0	20	0	20	0	20	0	20
Bray-1 P	Grain yield		Biomass yield		Grain P uptake		Total P uptake		P HI	
mg kg^{-1}	Mg ha^{-1}				kg ha^{-1}				kg kg^{-1}	
	Previous crop = soybean									
<10, n = 4†	12.80‡	13.73*	20.12§	21.82*	26.96	31.91**	30.04	34.70*	0.90	0.92
>10, n = 11	14.34	14.08‡	24.59	24.12	37.62	37.54	42.66	43.21	0.88	0.87
>20, n = 5	14.35	14.12	24.87	24.89	42.57	42.49	47.66	48.92	0.89	0.86*
	Previous crop = corn									
≤20, n = 9	13.99	14.69**	24.31	25.60***	30.86	35.60***	33.56	39.04***	0.92	0.91
>20, n = 5	14.46	14.32	26.72	26.25	30.34	31.58	32.52	34.98	0.93	0.90
	Previous crop = drybean									
P >20, n = 5	13.90	14.18	22.11	22.42	21.98	22.66	26.21	27.60	0.84	0.82
	Overall									
	14.04	14.23	23.90	24.24	31.41	33.47***	35.14	37.87***	0.89	0.88*

* P interaction was significant at P = 0.05.

** P interaction was significant at P = 0.01.

** P interaction was significant at P = 0.001.

† n = number of site-years.

‡ P interaction was significant at P = 0.1.

§ Treatment effects were not significant at P < 0.1 if significance is not indicated. Application of an additional 20 kg ha^{-1} P did not affect the overall means.

Table 4. The effect of 20 compared with 0 kg P ha^{-1} applied to corn in 34 trials conducted in Nebraska on yield components and P use efficiency.

Bray-1 P	Plants m^{-2}		Ears m^{-2}		Kernel ear^{-1}		Kernel m^{-2}		IE, kg kg^{-1}†		RIE, kg Mg^{-1}	
	0	20	0	20	0	20	0	20	0	20	0	20
mg kg^{-1}	P rate, kg ha^{-1}											
	Previous crop = soybean											
<10, n = 4†	7.30§	7.55‡	7.01	7.41**	495	512	3477	3802*	478	451	2.37	2.52
>10, n = 11	6.92	6.75*	6.79	6.68	579	578	3889	3817	389	375	2.92	3.03
>20, n = 5	6.92	6.85	6.85	6.85	567	560	3859	3816	310	297‡	3.32	3.43
	Previous crop = corn											
≤20, n = 9	7.39	7.49	7.33	7.40	548	567*	4011	4190*	430	387***	2.39	2.65***
>20, n = 5	7.37	7.26	7.32	7.22	522	511	3822	3770	467	420**	2.21	2.44*
	Previous crop = drybean											
P >20; n = 5	7.74	7.80	8.13	8.22	496	502	3999	4096	546	519	1.91	1.99

* Significant at P = 0.05.

** Significant at P = 0.01.

*** Significant at P = 0.001.

† Kernel weight was not affected by P application. IE is internal efficiency of P use expressed as grain produced per unit of aboveground plant nutrient uptake at physiological maturity. RIE is reciprocal internal efficiency expressed as amount of plant nutrient uptake per unit of grain produced. n = number of site-years.

‡ P effect was significant at P = 0.1.

§ Treatment effects were not significant at P < 0.1 if significance is not indicated. Application of an additional 20 kg ha^{-1} P did not affect the overall means.

of sites with the complex soil test equation. The threshold for response was 39 kg ha^{-1} of UP.

The P IE levels are generally high compared with those reported for corn by Janssen and de Willigen (2006) with their median value of 350 compared to 372 kg kg^{-1} (Table 2). The IE level for extremely concentrated P is comparable to that found for rice (*Oryza sativa* L.) (Witt et al., 1999) while the level at extreme dilution is 33% higher than for rice. There were trends of increased IE (r = 0.62) and decreased RIE (r = −0.52) of P use with increase in Bray-1 P when the previous crop was soybean. These trends were weaker when the previous crop was corn with r = 0.41 and −0.33 for IE and RIE, respectively. Application of P, compared with no P applied, resulted in decreased IE and increased RIE when the previous crop was corn (Table 4). The agronomic efficiency of use values for 20 kg ha^{-1} applied P were 0.23, 0.25, and 46.5 kg kg^{-1} of applied P for plant P, grain P, and grain yield, respectively, when the previous crop was soybean and Bray-1 P < 10. Corresponding values when the previous crop was corn and Bray-1 P was <20 were 0.27, 0.24, and 35.0 kg kg^{-1} of applied P for plant P, grain P, and grain yield, respectively.

The results suggest lower soil test P critical levels for corn following soybean compared with continuous corn. Bordoli and Mallarino (1998) reported yield increase with applied P only when Bray-1 P was less than 12 mg kg^{-1} for corn following soybean. Mallarino and Blackmer (1992) reported results for 24 trials including 9 and 16 with corn and soybean as the previous crop. For corn following soybean, their mean grain yield responses to 25 kg ha^{-1} P were 1.15, 0.50, and 0.01 Mg ha^{-1} when Bray-1 P was <10, 10 to 20, and >20 mg kg^{-1}, respectively. For corn following corn, their mean responses were 1.03 and 0.38 Mg ha^{-1} when Bray-1 P was <15 and ≥20 mg kg^{-1}, respectively. Dodd and Mallarino (2005), however, found the critical level for Bray-1 P for corn following soybean to be between 15 and 21 mg kg^{-1}.

Grain yield response of corn to applied P, relative to soil test P, was greater when the previous crop was corn compared with soybean. This may have been because of greater net release of P from SOM and crop residues when the previous crop was soybean. Crop residue was more when the previous crop was corn compared with soybean, but most corn after corn site-years had ridge or other tillage before planting. Therefore, lower soil temperature and slower root growth were not likely causes for the greater response to P when the previous crop was corn rather than soybean. Verma et al. (2005) found the net gain in ecosystem C under irrigation was near neutral with continuous corn but negative with the soybean-corn rotation. More P may be released and available to early crop growth with soybean residues compared with corn because of more decomposition, especially of leaves and nodules, during the late summer, fall, and early spring before planting corn. More organic P is likely mineralized during the growing season for corn following corn compared with corn following soybean, as indicated by soil surface CO_2 flux (Amos et al., 2007). This would supply more P during as compared with before the growing season. At Bray-1 P < 20 mg kg^{-1}, there is no evidence that the corn–arbuscular mycorrhizal association was more effective in plant P uptake with corn following soybean compared with continuous corn. Phosphorus uptake was less with corn following soybean, if the Brunswick 2003 site-year is excluded, even though mean grain yield was similar with no P applied for the two cropping systems.

Fertilizer P was surface-applied without incorporation for all site-years. While response to P might have been greater with incorporated or injected P, this is not likely as Wortmann et al. (2006a, 2006b) and Bordoli and Mallarino (1998) found similar responses with surface application compared with injected or incorporated.

An economic analysis illustrates the practical significance of the effect of the previous crop on response to P (Table 3). When Bray-1 P < 20 mg kg^{-1} and the preceding crop was corn, the fertilizer P/corn price ($ kg^{-1}) ratio needs to be less than 35 to pay for the purchase of broadcast-applied fertilizer P; a lower ratio will be needed to cover accompanying interest, procurement, application, and other costs. When the preceding crop was soybean and Bray-1 P < 10 mg kg^{-1}, the fertilizer P/corn price ($ kg^{-1}) ratio needs to be less than 45 to pay for the purchase of broadcast-applied fertilizer P. The results show that when Bray-1 P is above these levels, probability of economical yield gain during the year of application is very low, although there may be longer-term value in the maintenance of soil test P levels. When fertilizer P cost is high relative to other operational costs, band application at a half-rate may be preferred to broadcast application (Shapiro et al., 2003) or deferring broadcast P application to a future year with more favorable P prices might be considered.

Potassium

Three sites with loamy sand soil had soil test K levels below 125 mg kg^{-1}, the UN-L critical level for K application (Shapiro et al., 2003). Soil test K at 0- to 20-cm and 20- to 40- cm depths was highly correlated (Fig. 4b), agreeing with the findings of Olson et al. (1958). Soil test K accounted for only 11% of the variation in UK over all cropping systems when no K was applied. Prediction of soil K supply with no K applied was improved by including pH and SOM in the equation.

$$\text{UK (all cropping systems)} = 137.4 + 0.81\ \text{K} - 0.000531\ \text{K}^2 + 68.2\ \text{pH} - 8.70\ \text{pH}^2 - 57.9\ \text{SOM},\ R^2 = 0.28,\ n = 135$$

$$\text{UK (corn following corn)} = -1300 - 2.06\ \text{K} - 0.00158\ \text{K}^2 + 713.1\ \text{pH} - 78.3\ \text{pH}^2 - 2.16\ \text{SOM} - 0.888\ \text{SOM}^2 + 0.578\ \text{pH K},\ R^2 = 0.41,\ n = 52$$

$$\text{UK (corn following soybean)} = 212.6 + 0.304\ \text{K} - 0.547\ \text{SOM}^2,\ R^2 = 0.21;\ \text{or} = 201.1 + 0.226\ \text{K};\ R^2 = 0.17,\ n = 63$$

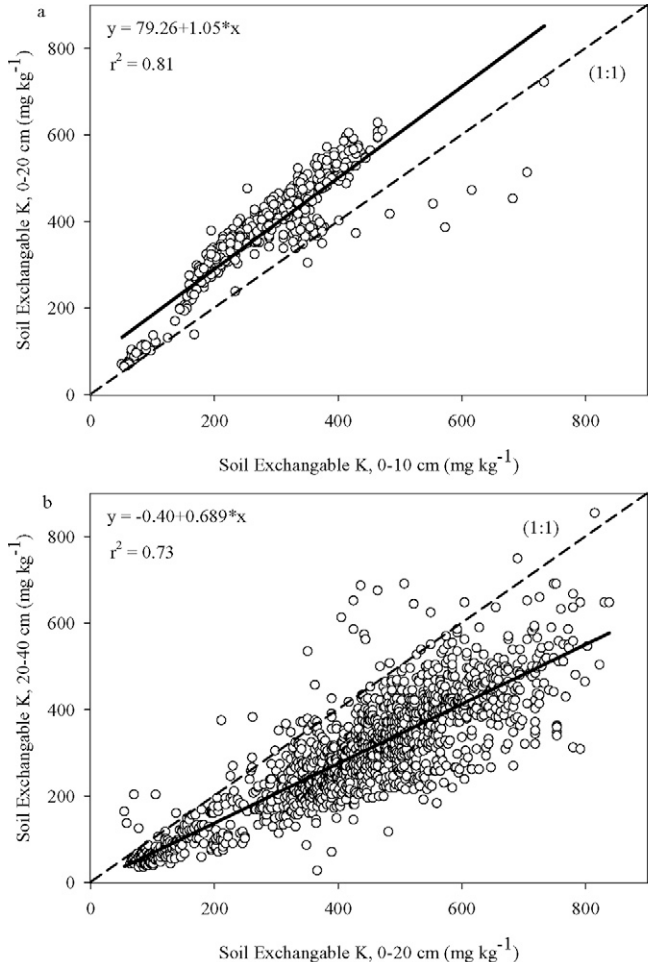

Fig. 4. The relationship of soil exchangeable K at 0- to 20-cm with (a) 0- to 10-cm depth (*n* = 468) and (b) 20- to 40-cm depth (*n* = 1458) for soil samples collected from 34 site-years in Nebraska.

Soil test K for the 0- to 10-cm and 20- to 40-cm depths was not significant in these models. As with soil test P, the R^2 values were often small but predictability of UK was greatly improved by considering soil organic matter and soil pH, as compared with soil test K alone. Application of K through irrigation at some sites may have reduced the predictability of UK.

There was no yield increase with K application and a small but significant mean yield decrease over all site-years (Table 5). The site-years with the greatest negative, although not always significant, effect of K application were Concord and Cairo in 2002, Mead in 2003, and Brunswick in 2004. Overall, grain and biomass yield and total K uptake were reduced by application of 40 kg ha^{-1} K. Internal K-use efficiency ranged from 83 to 28 kg grain kg^{-1} UK when plant K was extremely diluted or concentrated, respectively (Table 2). The K IE levels are generally low compared with those reported for corn by Janssen and de Willigen (2006), with a median value of 65 compared with 49 kg kg^{-1} in this study.

Table 5. The mean effect of 40 kg ha^{-1} K applied to corn in 34 trials conducted in Nebraska. Grain yield is expressed for 155 g kg^{-1} water content whereas other variables were determined on an oven-dry basis.

Previous crop	Grain yield, Mg ha^{-1}		Biomass yield, kg ha^{-1}		Plant K, kg ha^{-1}		100 kernel wt., g		IE, kg kg^{-1}†		RIE, kg Mg^{-1}	
	0	40	0	40	0	40	0	40	0	40	0	40
	K rate, kg ha^{-1}											
Soybean	14.38‡	13.99*	23.97	23.54	287.1	283.7	32.71	32.10*	53.8	53.2	19.8	20.1
Corn	14.75	14.57	26.12	25.80	345.5	341.1	31.71	32.69	46.7	46.5	23.6	23.5
Dry bean	14.16	14.18	23.36	22.41	285.9	261.9+	30.87	30.29	51.7	56.0	20.3	18.5
Overall	14.49	14.23*	24.70	24.24*	309.1	302.5	32.03	32.08	50.6	50.9	21.4	21.3

* Indicate that the effect of K application significant at $P = 0.05$.

† Indicate that the effect of K application significant at $P = 0.10$.

‡ Treatment effects for site-years are not significant at $P < 0.1$ if significance is not indicated. There were 15, 14, and 5 site-years for corn following soybean, corn, and dry bean, respectively. Application of an additional 40 kg ha^{-1} K did not affect the overall means. Other yield components were not affected by K application. Yield was significantly affected by K in site-year 4 only with a significant decrease in yield with K applied.

Mean crop K requirement can be estimated for the expected yield.

UK (all cropping systems) = 130.5 + 0.8635 GY^2, $R^2 = 0.28$, $n = 1484$

UK (corn following corn) = 92.8 + 16.84 GY, $R^2 = 0.16$, $n = 583$

UK (corn following soybean) = –75.9 + 26.55 GY, $R^2 = 0.41$, $n = 700$

Lack of responsive site-years in this study prevented verification of the value of the soil test equations as well as UK estimation based on yield for prediction of K responsive sites.

Internal efficiency of K use was not affected by K application but was relatively low when the previous crop was corn rather than soybean or dry bean. Internal efficiency decreased ($r = -0.30$) and RIE increased ($r = 0.25$) with increasing soil test K. The K IE levels for extremely diluted and concentrated K are low compared to those found for rice (Witt et al., 1999). The results confirm that the UN-L recommendation does not under-recommend K application.

Fertilizer K was broadcast-applied without incorporation, which has been shown to be as effective as deep or shallow banded K (Vyn et al., 2002) unless early season drought conditions occur (Bordoli and Mallarino, 1998). Such drought conditions did not occur in these irrigated trials. Yield depression with K application has been observed in other studies in Nebraska. Miany (1980) reported the yield depression with K application in eastern Nebraska but uptake of other nutrients was not affected. McCallister et al. (1987) suggested that the yield depression may be due to induced P deficiency. This may result from P reaction with cations released from the exchange complex following K application to form low solubility P compounds.

Sulfur

There was not a significant effect on yield with applied S at any of the 11 site-years where S rate treatments were included. Sulfur IE increased ($r = 0.56$) and RIE decreased ($r = -0.51$) with increasing soil test S across all site-years. Internal S-use efficiency ranged from 1070 to 310 kg grain kg^{-1} US when plant S was extremely diluted or concentrated, respectively, with a median of 610 kg kg^{-1} (Table 2). Typical crop S requirement can be estimated for an expected yield.

US (all cropping systems) = 1.841 + 1.483 × GY, $R^2 = 0.44$, $n = 1484$

US (corn following corn) = 11.18 + 0.0603 GY^2, $R^2 = 0.62$, $n = 583$

US (corn following soybean) = 2.998 + 1.442 GY, $R^2 = 0.41$, $n = 700$

For a grain yield of 15 Mg ha^{-1}, mean US is estimated to be 24 kg S ha^{-1}.

The results are consistent with the UN-L recommendation for medium and fine texture soil (Shapiro et al., 2003) and the findings of Wortmann et al. (2006a, 2006b), who did not observe a corn or grain sorghum response to applied S on medium and fine-texture no-till soils in eastern Nebraska. Soil organic matter was above 10 mg kg^{-1} for three of the five site-years with sandy soil and response to S was not expected. Site-year 3, Brunswick in 2002, was a likely place for yield response to S because of sandy soil, low soil organic matter, and low Ca-phosphate–extracted S, but the yield increase of 0.34 Mg ha^{-1} with S application was not significant.

Soil test information did not account for variation in US for the loamy sand soil when no S was applied. The interactions of soil S with SOM and pH were important in accounting for US on medium and fine-texture soils with no S applied:

US = 22.07– 0.175 pH S + 0.0478 SOM S; $R^2 = 0.28$, $n = 229$

Lack of responsive site-years in this study prevented verification of the value of the soil test equations as well as US estimation based on yield for prediction of S responsive sites.

CONCLUSION

This research was conducted across a wide range of temperate high yield corn production conditions and the results should be widely applicable to high yield corn production of similar day lengths. The results indicate a need to revise the critical level for Bray-1 P from 15 to 20 mg kg^{-1} for high-yield corn following corn but not for corn following soybean. Further research is needed to better understand the effect of previous crop on corn response to applied P. The Olsen soil P test is often used for alkaline soils in place of Bray-1, but Bray-1 and Olsen were closely related when soil pH was above 7.4 with an Olsen/Bray-1 P ratio of 0.59. Equations that consider soil organic matter and pH as well as soil test P, K, or S generally accounted for more variation in nutrient uptake than the nutrient tests alone. However, the more complex soil test equations were not better than soil test P thresholds for identifying P responsive site-years. The results confirm the UN-L recommendations for K and S that yield response to applied K is unlikely if soil test K is above 125 mg kg^{-1} and response to applied S is not likely on medium and fine-texture soils or on sandy soils with more than 10 mg kg^{-1} SOM. Use of soil analysis results to estimate the capacity of soil to supply K, and S for medium and fine-texture soil, may be improved by considering SOM and/or soil pH in the interpretation. Grain produced per unit of P and S uptake increased as soil test P and S increased, respectively, but K IE decreased as soil test K increased. Sulfur uptake can be better estimated from grain yield than can P and K uptake.

REFERENCES

Amos, B., H. Shen, T.J. Arkebauer, and D.T. Walters. 2007. Effect of previous crop residue on soil surface carbon dioxide flux in maize. Soil Sci. 172:589–597.

Bordoli, J.M., and A.P. Mallarino. 1998. Deep and shallow banding of phosphorus and potassium as alternatives to broadcast fertilization of no-till corn. Agron. J. 90:27–33.

Dodd, J.R., and A.P. Mallarino. 2005. Soil-test phosphorus and crop grain yield response to long-term phosphorus fertilization of corn–soybean rotations. Soil Sci. Soc. Am. J. 69:1118–1128.

Eghball, B., and D.H. Sander. 1989a. Band spacing effects of dual-placed nitrogen and phosphorus fertilizers on corn. Agron. J. 81:178–184.

Eghball, B., and D.H. Sander. 1989b. Distance and distribution effects of phosphorus fertilizer on corn. Soil Sci. Soc. Am. J. 53:282–287.

Eghball, B., D.H. Sander, and J. Skopp. 1990. Diffusion, adsorption and predicted longevity of banded phosphorus fertilizer in three soils. Soil Sci. Soc. Am. J. 54:1161–1165.

Fawzi, M.A.H.A., and J.V. Drew. 1966. The importance of illite as a source of potassium in Nebraska soils. Soil Sci. Soc. Am. Proc. 30:242–245.

Fox, R.L., R.A. Olson, and H.F. Rhoades. 1964. Evaluating the sulfur status of soils by plant and soil tests. Soil Sci. Soc. Am. Proc. 28:243–246.

Garcia, J.P., C.S. Wortmann, M. Mamo, R.A. Drijber, J.A. Quincke, and D. Tarkalson. 2007. One-time tillage of no-till: Effects on nutrients, mycorrhizae, and phosphorus uptake. Agron. J. 99:1093–1103.

Janssen, B.H., F.C.T. Guiking, D. van der Eijk, E.M.A. Smaling, J. Wolf, and H. van Reuler. 1990. A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). Geoderma 46:299–318.

Janssen, B.H., and P. de Willigen. 2006. Ideal and saturated soil fertility as bench marks in nutrient management: I. Outline of the framework. Agric. Ecosyst. Environ. 116:132–146.

Mallarino, A.P., and A.M. Blackmer. 1992. Comparison of methods for determining critical concentrations of soil test phosphorus for corn. Agron. J. 84:850–856.

Mallarino, A.P., and A.M. Blackmer. 1994. Profit-maximizing critical values of soil-test potassium for corn. J. Prod. Agric. 7:261–268.

Mallarino, A.P., and R. Borges. 2006. Phosphorous and potassium distribution in soil following long-term deep-band fertilization in different tillage systems. Soil Sci. Soc. Am. J. 70:702–707.

McCallister, D.L., C.A. Shapiro, W.R. Raun, F.N. Anderson, G.W. Rehm, O.P. Engelstad, M.P. Russelle, and R.A. Olson. 1987. Rate of phosphorus and potassium buildup/decline with fertilization for corn and wheat on Nebraska Mollisols. Soil Sci. Soc. Am. J. 51:1646–1652.

Miany, F. 1980. Crop and soil response to applied P and K in a long term buildup/depletion study. M.S. thesis. Univ. of Nebraska, Lincoln.

Missouri Agricultural Experiment Station. 1998. Recommended chemical soil test procedures for the North Central Region. North Central Regional Publ. 221. Missouri Agric. Exp. Stn., Columbia MO.

Olson, R.A., F.N. Anderson, K.D. Frank, P.H. Grabouski, G.W. Rehm, and C.A. Shapiro. 1987. Soil testing interpretations: Sufficiency vs. build-up and maintenance. SSSA Special Publ. 21. p. 41–52. In J.R. Brown (ed.) Soil testing: Sampling, correlation, calibration, and intepretation. SSSA, Madison,WI.

Olson, R.A., A.F. Dreier, and R.C. Sorensen. 1958. The significance of subsoil and soil series in Nebraska soil testing. Agron. J. 50:185–188.

Olson, R.A., K.D. Frank, P.H. Grabouski, and G.W. Rehm. 1982. Economic and agronomic impacts of varied philosophies of soil testing. Agron. J. 74:492–499.

Olson, R.A., M.B. Rhodes, and A.F. Dreier. 1954. Available phosphorus status of Nebraska soils in relation to series classification, time of sampling and method of measurement. Agron. J. 46:175–180.

Raun, W.R., D.H. Sander, and R.A. Olson. 1987. Phosphorus fertilizer carriers and their placement for minimum till corn under sprinkler irrigation. Soil Sci. Soc. Am. J. 51:1055–1062.

Rehm, G.W. 1978. Sulfur fertilization of alfalfa and corn on sandy soils of Nebraska. Res. Bull. 284. Univ. of Nebraska, Lincoln.

Rehm, G.W. 1984. Source and rate of sulfur for corn production. J. Fert. Issues 3:99–103.

Rehm, G.W. 1993. Timing sulfur applications for corn (*Zea mays* L.). Commun. Soil Sci. Plant Anal. 24:285–294.

Rehm, G.W. 2000. Do we really need a soil test for sulfur? p. 66–69. *In* Proc. 30th North Central Extension–Industry Soil Fertility Conference. Potash and Phosphate Institute, St. Louis, MO.

Rehm, G.W., S.D. Evans, W.W. Nelson, and G.W. Randall. 1988. Influence of placement of phosphorus and potassium on yield of corn and soybeans. J. Fert. Issues 5:6–13.

Rehm, G.W., and R.C. Sorensen. 1985. Effects of potassium and magnesium applied for corn grown on an irrigated sandy soil. Soil Sci. Soc. Am. J. 49:1446–1450.

Rehm, G.W., R.C. Sorensen, and R.A. Wiese. 1981. Application of phosphorus, potassium, and zinc to corn grown for grain or silage: Early growth and yield. Soil Sci. Soc. Am. J. 45:523–528.

Rehm, G.W., R.C. Sorensen, and R.A. Wiese. 1983. Application of phosphorus, potassium, and zinc to corn grown for grain or silage: Nutrient concentration and uptake. Soil Sci. Soc. Am. J. 47:697–700.

Shapiro, C.A., R.B. Ferguson, G.W. Hergert, A. Dobermann, and C.S. Wortmann. 2003. Fertilizer suggestions for corn. NebGuide G74-174-A. Univ. of Nebraska Coop. Ext. Service, Lincoln.

Sleight, D.M., D.H. Sander, and G.A. Peterson. 1984. Effect of fertilizer phosphorus placement on the availability of phosphorus. Soil Sci. Soc. Am. J. 48:336–340.

USDA-NASS. 2008. United States Department of Agriculture–National Agricultural Statistics Service. Available at http://www.nass.usda.gov (accessed June 2008; verified 4 Feb. 2009).

Verma, S.B., A. Dobermann, K.G. Cassman, D.T. Walters, J.M. Knops, T.J. Arkebauer, A.E. Suyker, G.G. Burba, B. Amos, H. Yang, D. Ginting, K.G. Hubbard, A.A. Gitelson, and E.A. Walter-Shea. 2005. Annual carbon dioxide exchange in irrigated and rainfed maize-based agroecosystems. Agric. For. Meteorol. 131:77–96.

Vyn, T.J., D.M. Galic, and K.J. Janovicek. 2002. Corn response to potassium placement in conservation tillage. Soil Tillage Res. 69:159–169.

Webb, J.R., A.P. Mallarino, and A.M. Blackmer. 1992. Effects of residual and annually applied phosphorus on soil test values and yields of corn and soybean. J. Prod. Agric. 5:148–152.

Witt, C., A. Dobermann, S. Abdulrachman, H.C. Gines, W. Guanghuo, R. Nagarajan, S. Satawatananont, T.T. Son, P.S. Tan, L.V. Tiem, G.C. Simbahan, and D.C. Olk. 1999. Internal nutrient efficiencies of irrigated lowland rice in tropical and subtropical Asia. Field Crops Res. 63:113–138.

Wortmann, C.S., S.A. Xerinda, M. Mamo, and C.A. Shapiro. 2006a. No-till row crop response to starter fertilizer in eastern Nebraska: I. Irrigated and rainfed corn. Agron. J. 98:156–162.

Wortmann, C.S., S.A. Xerinda, and M. Mamo. 2006b. No-till row crop response to starter fertilizer in eastern Nebraska: II. rainfed grain sorghum. Agron. J. 98:187–193.