Sims, J.L., and K.L. Wells. 1985. Liming and fertilizing burley tobacco. Ky. Agric. Exp. Stn. Bull. AGR-49.
Turner, F.T., and M.F. Jund. 1994. Assessing the nitrogen requirements of rice crops with a chlorophyll meter. Aust. J. Exp. Agric. 34: 1001–1005.
Vogelmann, T.C. 1989. Penetration of light into plants. Photochem. Photobiol. 50:895–902.
Wood, C.W., D.W. Reeves, R.R. Duffield, and K.L. Edmisten. 1992a. Field chlorophyll measurements for evaluation of corn nitrogen status. J. Plant Nutr. 15:487–500.
Wood, C.W., P.W. Tracy, D.W. Reeves, and K.L. Edmisten. 1992b. Determination of cotton nitrogen status with a hand-held chlorophyll meter. J. Plant Nutr. 15:1435–1448.

Deep and Shallow Banding of Phosphorus and Potassium as Alternatives to Broadcast Fertilization for No-Till Corn

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ABSTRACT

Proper P and K management for no-till crops is uncertain. Potential problems include inappropriate extrapolation of soil test interpretations and fertilizer recommendations from conventional tillage, inappropriate soil sampling techniques, and inefficient fertilizer placement. This study compared broadcast, deep-band, and planter-band P and K placements for no-till corn (*Zea mays* L.). Long-term P and K trials were established in 1994 at five Iowa research centers and were evaluated for 3 yr. Eleven short-term P–K trials were established in farmers' fields during the same period. Treatments were various P (0 to 56 kg P ha^{-1}) and K (0 to 132 kg K ha^{-1}) rates broadcast, banded with the planter 5 cm beside and below the seeds, and deep-banded at the 15- to 20-cm depth before planting. Soil samples were collected from the 0- to 7.5-cm and 7.5- to 15-cm depths prior to planting. Soil-test P (P_{ST}) at the 0- to 15-cm depth ranged from very low to very high across sites; soil-test K (K_{ST}) ranged from optimum to very high. There were grain yield responses to fertilization at several sites, but no significant differences between the P or K rates and no interactions between rates and placements. Phosphorus increased yields only in soils testing very low or low, and there was no response to P placement at any site. Potassium increased yields in several soils that tested optimum or higher in K_{ST}, and yields were higher when K was deep-banded. High rates of broadcast or planter-banded K did not offset the advantage of deep-banded K. Responses were better related with deficient rainfall in late spring and early summer than with K_{ST}. Current soil-test P interpretations and P fertilizer recommendations based on chisel-plow tillage are appropriate for most Iowa soils managed with no-tillage. Further work is needed to better characterize and predict responses to deep-banded K. Because yield response was small, the cost-effectiveness of deep-band K will be determined largely by application costs.

NO-TILL CORN PRODUCTION in Iowa and many regions of the U.S. Corn Belt increased markedly during the late 1980s and early 1990s, but remained constant or decreased thereafter (CTIC, 1996). Several factors may explain this trend. Among these, although not necessarily the most important, is farmers' uncertainty about appropriate fertilization management. Potential problems with P and K management include inappropriate extrapolation of soil test interpretations and fertilizer recommendations from other tillage systems, inappropriate soil sampling techniques (e.g., in terms of sampling depth and location relative to crop rows or fertilizer bands), and inefficient fertilizer placement. These problems could arise because of changes in nutrient availability at different soil depths, soil temperature and water relations, and root growth and distribution, among other factors.

No-till management usually leads to P and K stratification in soils. Both nutrients accumulate in the soil surface as a result of minimal mixing of surface-applied fertilizers and crop residues with soil, limited vertical movement of P and K in most soils, and cycling of nutrients from deep soil layers to shallow layers through nutrient uptake by roots (Shear and Moschler, 1969; Griffith et al., 1977; Ketchenson, 1980; Mackay et al., 1987; Karathanasis and Wells, 1990; Karlen et al., 1991). Furthermore, reduced P sorption and K retention by soil constituents in surface layers of no-till soils (Karathanasis and Wells, 1990; Guertal et al., 1991) may contribute to higher soil test values in this zone. A relative accumulation of P and K near the soil surface may decrease nutrient availability to plants because of the increased likelihood of dry conditions in this zone. High residue coverage (a characteristic of no-tilled soils), however, usually increases soil moisture and reduces soil temperature at shallow depths. Early in the season this may inhibit plant growth and nutrient availability, but in drier periods it can also increase root activity (Barber, 1971).

Several reports showed infrequent and small decreases in nutrient availability due to nutrient stratification in high-rainfall areas of the Corn Belt (Singh et al., 1966; Moschler and Martens, 1975; Belcher and Ragland, 1972). Other work (Eckert and Johnson, 1985; Yibirin et al., 1993), however, showed that shallow subsurface banding (5 cm beside and below the seeds) can significantly increase P and K fertilizer use efficiency compared with broadcast fertilization for no-till corn. This result can be explained by the effects of banding in minimizing retention of these nutrients by soil constituents and in increasing fertilizer use efficiency by crops. It also agrees with responses to starter fertilizers, which sometimes occur even in high-testing soils and often are attributed to P (Randall and Hoeft, 1988).

Deep placement of nutrients below the first 5 to 10 cm of the soils should be superior to other placements when nutrient stratification, coupled with topsoil mois-

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Abbreviations: K_{ST}, soil-test K; P_{ST}, soil-test P.

ture deficit, reduces nutrient uptake from shallow soil layers. Published research comparing deep-banding with other placements for no-till corn is scarce and inconsistent, however. Timmons et al. (1984) showed that deep banding (15-cm depth) of an N–P–K mixture produced higher yields of no-till corn than broadcast or other banded placements under dry conditions on an Iowa soil testing low in P. Other research (Farber and Fixen, 1986; Rehm, 1986) showed that planter-band placement is more efficient than deep-band placement for P and suggests that deep-banded nutrients may not alleviate early nutrient deficiency in conservation tillage systems. Mengel et al. (1988) showed that deep banding enhanced early growth and K uptake of no-till corn compared with other placements, but did not increase grain yields.

Inconsistencies in the available literature could be explained by complex interactions of fertilizer placement with soil and crop management factors and climate. The objective of this study was to compare broadcast, deep-band, and planter-band placement of P and K for no-till corn grain production in numerous fields with varied histories of no-till management and during three years that encompassed a wide variety of climatic conditions.

MATERIALS AND METHODS

Sites and Crop Management

The study included long-term trials and short-term, 1-yr trials. Ten long-term trials, five for P and five for K, were established in 1994 at five Iowa State University research centers and were evaluated through 1996. The sites were the Northeast Iowa Research Center near Nashua, the Northern Iowa Research Center near Kanawha, the Northwest Iowa Research Center near Sutherland, the Armstrong Southwest Research Center near Atlantic, and the Southeast Iowa Research Center near Crawfordsville. A corn–soybean [*Glycine max* (L.) Merr.] rotation was established at each trial by planting both crops each year on adjacent sections of the experimental areas. (The present report is limited to data for corn.) Eleven short-term P–K response trials also were established at farmers' fields in several regions of the state from 1994 through 1996. Corn was always planted after soybean. Data on the soils and some management practices used are shown in Table 1. The corn hybrids and planting dates used were among those recommended for each location. Crop management practices (except for N, P, and K fertilization) were those normally used by each farmer or at each research center. No field had received deep-banded P or K fertilization in the past.

Trials and Treatments

Long-Term Trials: Research Centers

There were eight treatments at each P or K trial. Six treatments were the factorial combinations of two fertilization rates and three placements, and two were nonfertilized controls. Fertilizer rates were 14 and 28 kg P ha^{-1} (triple superphosphate) at P trials and 33 and 66 kg K ha^{-1} (KCl) at K trials. The placements were side-banded with the planter (S), broadcast (B), and deep-banded (D). The planter bands were approximately 25 mm in width and were placed 5 cm to the side of and 5 cm below the seeds. The broadcast fertilizer was spread onto the soil surface by hand. The deep bands were approximately 25 mm in width and were placed 15 to 20 cm below the soil surface and spaced 0.76 m. The deep-bander had

Table 1. Site description, tillage history, and hybrid and planting date for 1- to 3-yr trials in a study of P and K fertilizer placement for no-till corn in Iowa.

Site	Year	Location†	Soil classification‡ Series	Soil classification‡ Great Group	pH	Years NT§	Hybrid¶	Planting date	Rainfall May	Rainfall June	*T*
						no.			mm	mm	°C
1	1994	NERC	Kenyon	Typic Hapludoll	7.1	1	GH-2390	26 Apr.	70	167	15.0
2	1995				7.2	2	P-3563	6 May	61	171	13.6
3	1996				7.2	3	P-3563	6 May	109	131	12.2
4	1994	NIRC	Webster	Typic Haplaquoll	6.9	1	P-3563	11 May	56	176	15.6
5	1995				7.2	2	NK-4242	5 May	123	106	13.8
6	1996				7.2	3	NK-4242	17 May	123	118	13.8
7	1994	NWRC	Galva	Typic Hapludoll	6.4	3	P-3417	10 May	54	185	16.1
8	1995				6.3	4	P-3751	22 May	137	126	12.6
9	1996				6.3	5	P-3563	1 May	75	161	12.7
10	1994	SERC	Mahaska	Aquic Argiudoll	6.2	1	MG-6890	10 May	72	114	16.4
11	1995				6.1	2	P-3417	7 May	177	114	15.6
12	1996				6.1	3	GH-2530	24 May	308	82	15.3
13	1994	SWRC	Marshall	Typic Hapludoll	6.0	1	GH-2525	5 May	15	220	17.6
14	1995				6.0	2	L-2719	17 May	178	81	13.8
15	1996				6.0	3	GL-5962	24 Apr.	250	176	14.6
16	1994	Wellman	Nevin	Aquic Argiudoll	7.1	3	DK-591	22 Apr.	53	139	16.2
17	1994	Manning	Colo	Cumulic Argiudoll	6.0	7	R-6348	22 Apr.	42	216	18.3
18	1995	Wellman	Givin	Udollic Ochraqualf	7.0	6	DK-580	22 May	162	123	14.8
19	1995	Manning	Marshall	Typic Hapludoll	6.4	7	R-6235	19 May	93	81	16.8
20	1995	Manning	Marshall	Typic Hapludoll	6.3	3	R-6235	19 May	110	69	16.8
21	1995	Ames	Nicollet	Aquic Hapludoll	7.4	4	P-3489	18 May	110	88	14.4
22	1995	Wellman	Nevin	Aquic Argiudoll	7.0	3	DK-580	7 May	321	56	14.8
23	1996	Parkesburg	Dinsdale	Typic Argiudoll	7.0	6	L-5248	16 May	133	70	13.1
24	1996	Wellman	Nevin	Aquic Argiudoll	7.1	5	DK-626	22 Apr.	321	56	13.7
25	1996	Wellman	Nevin	Aquic Argiudoll	7.1	5	DK-626	22 Apr.	321	56	13.7
26	1996	Manning	Marshall	Typic Hapludoll	6.0	9	DK-580	24 Apr.	152	216	14.5

† NERC, NIRC, NWRF, SERF, and SWRF indicate the northeast, north, northwest, southeast, and southwest Iowa research farms (3-yr, long-term research center trials). Other names indicate the nearest city to the trials.
‡ Soil classifications are as of the start of the study. Several soil series have since been reclassified: Colo, Cumulic Endoaquoll; Givin, Udollic Endoaqualf; Mahaska, Aquertic Argiudoll; Webster, Typic Endoaquoll.
§ NT, years under no-till.
¶ Corn hybrid: DK, DeKalb; GH, Golden Harvest; GL, Great Lakes; L, Lynks; MG, Mycogen; NK, Northrup King; P, Pioneer; R, Renze.
# *T*, average air temperature in May.

a coulter–knife combination that tilled and removed residues from a strip 12 to 18 cm in width. In one control (B0), the soil and residue were not disturbed; in the other (empty knife, or D0), plots received a coulter–knife pass of the bander without any fertilizer. Plot size varied slightly among sites. Plot width varied from 4.5 to 6.1 m (six or eight rows spaced 0.76 cm); the length varied from 16 to 18 m.

The treatments were applied for both crops each year. Thus, treatment effects on corn measured in 1995 and 1996 likely were the result of the recent applications plus any residual effects from previous applications. The broadcast and deep-banded treatments for the 1994 and 1995 crops were applied in spring, 3 to 5 wk before planting; for the 1996 crop, they were applied in the previous fall (in November 1995). Corn on plots corresponding to the deep-band treatment was planted on top of the coulter–knife tracks. Nonlimiting K fertilization (280 kg K ha^{-1}) was applied one-third broadcast and two-thirds deep-banded in spring 1994 at all P trials. Nonlimiting P fertilization (120 kg P ha^{-1}) was applied one-third broadcast and two-thirds deep-banded in spring 1994 at all K trials. Nitrogen fertilizer was applied at rates 50% higher than local recommendations.

Completely randomized block designs with three replications were used for all trials. The treatment sums of squares were partitioned into orthogonal comparisons of the controls (B0 vs. D0) and the mean of the controls vs. the mean of the fertilized treatments. The sums of squares of fertilized treatments were further partitioned into a factorial arrangement of placement, rate, and interaction effects. The means of the three placements were compared by LSD ($P \leq 0.05$) when the placement main effect was significant ($P \leq 0.05$).

Short-Term Trials: Farmers' Fields

Two trials were conducted in 1994, five in 1995, and four in 1996. There were 12 treatments in 1994, and 14 in 1995 and 1996. In 1994, treatments were four nonfertilized controls, the factorial combinations of two P rates and two placements (four), and the factorial combinations of two K rates and two placements (four). Two of the control treatments were absolute controls (B0) and the other two received a coulter–knife pass of the deep-bander without applying fertilizer (empty knife or D0). The fertilization rates were 14 or 56 kg P ha^{-1} (triple superphosphate) and 33 or 132 kg K ha^{-1} (KCl). The broadcast and deep-band placements were similar to those used at the research centers and in 1994 were applied in early spring. Plot width varied from 4.5 to 7.7 m (six or eight rows spaced 0.76 or 0.96 m); the length varied from 16 to 18 m.

The trials conducted in 1995 and 1996 received the same 12 treatments used in 1994, plus two additional treatments: a combination of 56 kg P ha^{-1} and 132 kg K ha^{-1}, either broadcast or deep-banded. Another important difference for trials conducted in 1995 and 1996 was that all treatments were applied in the previous fall (in November 1994 and 1995 for the 1995 and 1996 growing seasons, respectively). Two of the 1996 trials (Sites 25 and 26) included evaluation of residual effects of similar treatments that had been applied for 1995 soybean crops (no P and K fertilizers were applied for the 1996 corn crop).

Completely randomized block designs with three replications were used for all trials. The treatment sums of squares were partitioned into orthogonal comparisons of the controls (B0 vs. D0), the mean of all controls vs. the mean of all fertilized treatments, a P rate × placement factorial (two rates, two placements, and the interaction effects), and a similar K rate × placement factorial. In addition, to better estimate separate responses to P or K fertilization, the treatment sums of squares were partitioned into two nonorthogonal comparisons that compared the mean of all controls with the mean of plots receiving only P and the mean of all controls with the mean of plots receiving only K. An additional LSD ($P \leq 0.05$) test was used for trials conducted in 1995 and 1996 to compare yields of equivalent P and K rates applied separately or combined when the treatment main effect or the orthogonal comparisons suggested significant responses to either nutrient.

Measurements

Soil samples were collected from the experimental areas before the treatments were first applied. Composite soil samples (72 cores, 2-cm diameter each) were collected randomly from five depths (0–7.5, 7.5–15, 15–30, 30–60, and 60–90 cm). In addition, in 1995 and 1996, the absolute control plots (B0) of trials at research centers were sampled to depths of 0 to 7.5 cm and 7.5 to 15 cm by collecting composites made up of 12 soil cores. Soil was analyzed for K_{ST} by the ammonium acetate method, P_{ST} by the Bray-1 method, and pH following procedures recommended for the North Central region (North Dakota Agric. Exp. Stn., 1988). Soil-test P and K values are shown in Table 2 for the two shallower depths sampled. Subsoil data are not shown, because most values were low according to Iowa State University interpretations for subsoils. Iowa State University soil-test interpretations (Voss et al., 1996) for samples collected from the 0- to 15-cm depth and low subsoil P and K are used in this report. Boundaries for the P_{ST} classes are (mg kg^{-1}): 8, very low; 16, low; 20, optimum; 30, high; >30, very high. The corresponding boundaries for K_{ST} are 60, 90, 130, 170, and >170 mg kg^{-1}, respectively.

Corn grain was harvested with plot combines from the center of each plot (15-m length of three or four rows) at research farms and by hand (7.5-m length of two rows) at farmers' fields. Yields were corrected to 155 g kg^{-1} moisture. Plant population was measured at harvest on two center rows of each plot.

RESULTS

The study encompassed a wide variety of growing conditions, and mean yields at each site ranged from 6.00 to 12.72 Mg ha^{-1} among sites. Study of yield responses at research farms or farmers' fields showed that there were no significant differences ($P \leq 0.05$) between the two P fertilization rates and the two K fertilization rates, and no significant interaction among rates and placements for either nutrient at any site. Furthermore, for farmers' field trials conducted in 1995 and 1996, comparisons of the P–K mixture with similar but separate P or K rates indicated nonsignificant P × K interactions at all sites. Because of these results, and to simplify the presentation and discussion of data, only placement means are reported for both nutrients and all trials. Plant population data and analysis are not shown, because treatments did not affect plant population at any site and because the use of plant population in covariance analysis of grain yields did not change the significance of treatment effects at any trial.

Responses to Fertilization and Placement

Long-Term Trials: Research Centers

Phosphorus fertilization increased yields ($P \leq 0.05$) in five site-years with very low or low P_{ST}, although responses did not occur for all low-testing soils (Table 3). The P placement method did not affect yields significantly ($P \leq 0.05$) at any site. The analysis of means

Table 2. Soil test P and K values for 26 sites in a study of P and K fertilizer placement for no-till corn in Iowa.†

Site	Soil test P 0–7.5 cm	Soil test P 7.5–15 cm	Soil test P 0–15 cm	Soil test P Class‡	Soil test K 0–7.5 cm	Soil test K 7.5–15 cm	Soil test K 0–15 cm	Soil test K Class
	mg kg^{-1}				mg kg^{-1}			
1	41	29	35	VH	160	105	133	H
2	36	30	33	VH	157	125	141	H
3	29	18	23	H	135	95	115	O
4	13	11	12	L	138	110	124	O
5	10	7	9	L	127	113	120	O
6	11	10	11	L	190	172	181	VH
7	10	6	8	VL	178	136	157	H
8	10	4	7	VL	229	181	205	VH
9	8	6	7	VL	309	215	262	VH
10	28	20	24	H	138	118	128	O
11	22	14	18	O	157	109	133	H
12	19	12	15	L	163	127	145	H
13	25	8	17	O	321	201	261	VH
14	23	11	17	O	295	178	237	VH
15	24	9	17	O	295	142	219	VH
16	29	19	24	H	124	92	108	O
17	14	8	11	L	259	149	204	VH
18	40	21	31	VH	331	181	256	VH
19	10	6	8	VL	162	138	150	H
20	15	9	12	L	215	167	191	VH
21	9	4	7	VL	121	88	105	O
22	31	18	25	H	147	119	133	H
23	7	4	5	VL	138	93	116	O
24	15	9	12	L	105	79	92	O
25	11	7	9	L	106	94	100	O
26	12	6	9	L	184	120	152	H

† For sites 1 to 15 (research center trials), P and K data are from adjacent separate P and K trials.
‡ VL, L, O, H, and VH: Iowa State University soil test interpretations very low, low, optimum, high, and very high.

over all sites showed a significant response to P and nonsignificant response to placement. The response to P over all sites can be explained by large responses at responsive sites and small (nonsignificant) trends at other sites. The P rate × site interaction was significant ($P \leq 0.05$, not shown), however, which confirms the lack of significant responses at some sites (i.e., mostly those testing optimum or above in P). The two controls differed only at Site 7, in which the coulter and knife pass increased yields slightly.

Potassium fertilization increased grain yields significantly ($P \leq 0.05$) at four sites (Table 4). These responses were not expected, because all soils tested optimum or higher in K_{ST}. The K placements differed only at Site 14, where the deep-band placement produced higher yields than other placements. When data from all sites were combined, however, responses to both K fertilization and placement were significant. The deep-band placement produced slightly higher yields (approximately 0.2 Mg ha^{-1} more) than other placements. The K response × site interaction was significant, which confirms that responses occurred at some sites but not in others. The finding that significant responses to placement occurred at only a few sites is in contrast with the significance of placement in the analysis over sites; however, this can be explained by the small yield advantage for the deep-band placement at many sites. The two controls differed at Sites 8 and 14, in which the

Table 3. Yield of corn as affected by P fertilization and placement (3-yr, long-term trials, Iowa research centers).

Site	Grain yield† B0	Grain yield† D0	Grain yield† B	Grain yield† D	Grain yield† S	Statistics ($P \leq F$)‡ CONT	Statistics ($P \leq F$)‡ FERT	Statistics ($P \leq F$)‡ PLACE
	Mg ha^{-1}							
1	8.29	8.19	8.47	8.45	9.02	0.98	0.26	0.39
2	6.98	6.16	6.70	7.19	6.74	0.15	0.34	0.38
3	10.21	10.05	10.09	9.98	9.94	0.66	0.54	0.83
4	9.73	9.47	10.10	10.16	9.95	0.32	0.01	0.31
5	8.66	8.86	9.12	9.46	9.14	0.64	0.07	0.47
6	8.93	8.79	9.45	9.51	9.54	0.71	0.01	0.94
7	7.78	8.76	8.84	8.55	9.02	0.01	0.01	0.21
8	6.03	6.39	7.07	6.95	6.89	0.29	0.01	0.75
9	4.80	5.65	7.39	7.58	7.76	0.20	0.01	0.73
10	9.69	9.36	9.46	9.65	9.94	0.53	0.60	0.43
11	8.03	8.38	8.06	8.57	7.84	0.43	0.85	0.08
12	9.51	9.58	9.43	9.50	9.48	0.89	0.80	0.98
13	10.57	10.44	10.81	10.50	10.38	0.80	0.84	0.50
14	10.62	10.69	10.21	10.46	10.25	0.86	0.15	0.63
15	9.49	9.95	9.83	9.65	9.49	0.20	0.76	0.40
Means	8.62	8.71	9.00	9.08	9.03	0.52	0.01	0.76

† B0, absolute control; D0, control with a coulter-knife pass; B, broadcast; D, deep-band; S, starter. All are means of two fertilization rates.
‡ CONT, comparison of the two controls; FERT, comparison of controls vs. fertilized treatments; PLACE, placement main effect. Differences between P rates and the interaction of rate vs. placement never were significant ($P \leq 0.05$).

Table 4. Yield of corn as affected by K fertilization and placement (3-yr, long-term trials, Iowa research centers).

	Grain yield†					Statistics ($P \leq F$)‡		
Site	B0	D0	B	D	S	CONT	FERT	PLACE
	Mg ha^{-1}							
1	8.48	8.35	8.48	8.69	8.22	0.80	0.99	0.46
2	6.76	6.98	6.78	7.01	6.87	0.45	0.90	0.53
3	10.16	9.77	9.92	10.15	9.78	0.26	0.94	0.31
4	10.23	10.06	10.24	10.68	10.73	0.55	0.11	0.29
5	9.42	9.40	9.55	9.95	9.87	0.96	0.05	0.18
6	9.66	9.44	9.74	9.85	9.90	0.55	0.21	0.81
7	10.30	10.02	9.84	10.30	10.07	0.37	0.61	0.13
8	6.66	7.01	7.09	7.08	6.97	0.05	0.04	0.53
9	7.70	7.03	7.31	7.61	7.19	0.08	0.98	0.26
10	10.57	10.09	10.56	10.61	10.24	0.29	0.58	0.44
11	8.23	8.17	8.28	8.61	8.25	0.89	0.44	0.36
12	8.61	8.73	9.50	10.02	9.60	0.75	0.01	0.16
13	10.34	10.14	10.14	10.08	10.36	0.65	0.85	0.63
14	9.06	9.71	9.76	10.25	9.40	0.05	0.03	0.01§
15	9.93	9.11	9.86	9.93	9.76	0.10	0.24	0.88
Means	9.07	8.93	9.14	9.39	9.15	0.18	0.01	0.01§

† B0, absolute control; D0, control with coulter-knife pass; B, broadcast; D, deep-band; and S, starter. All are means of two fertilization rates.
‡ CONT, comparison of the two controls; FERT, comparison of controls vs. fertilized treatments; PLACE, placement main effect.
§ The yield for the deep-band placement was higher than yields for the broadcast and planter-band placements (LSD, $P \leq 0.05$). Differences between K rates and the interaction of rate vs. placement never were significant ($P \leq 0.05$).

coulter and knife pass increased yields slightly compared with the absolute control.

Short-Term Trials: Farmers' Fields

Phosphorus fertilization increased yields ($P \leq 0.05$) at three sites with low or very low P_{ST}, although responses did not occur for all low-testing soils (Table 5). The P placements did not affect yields at any site. The effect of P fertilization was significant across all sites, perhaps due to the sum of small responses to P at several sites (often statistically nonsignificant).

Potassium fertilization increased yields at three sites and deep-banded K produced higher yields than broadcast K at one site (Table 5). The yield increases to both K fertilization and K placement were small, however. Similar to results observed at the research farms, responses to K fertilizer occurred even at sites testing high in K_{ST}. It is noteworthy that yields for deep-banded K were higher than for broadcast K at most sites, although the differences achieved statistical significance only at Site 19. Responses to both K fertilization and placement were statistically significant across all sites. Similarly to trials at research centers, the small yield advantages for deep-band placement at many sites explain the significance of placement in the analysis over all sites. The two controls differed at only one site, in which the coulter and knife pass increased yields slightly.

DISCUSSION

Results from long-term trials at research farms and short-term trials at farmers' fields showed that grain yield responses to P fertilization occurred only on some low-testing soils. There was no response to P placement at any site. The soils differed in the stratification of P_{ST} (Table 2), which reflects the differences in histories of no-till management and P fertilization. On average, the soils had 75% more P_{ST} in the 7.5-cm depth than in the 7.5- to 15-cm depth and the range across sites was 10 to 213%. Responses to P placement, however, were not

Table 5. Yield of corn as affected by P and K fertilization and placement (1-yr, short-term trials, Iowa farmers' fields).

	Grain yield†						Statistics ($P \leq F$)‡				
	Controls		P placement		K placement			P responses		K responses	
Site	B0	D0	PB	PD	KB	KD	CONT	FERT	PLACE	FERT	PLACE
	Mg ha^{-1}										
16	12.72	12.30	12.90	12.65	13.19	12.53	0.61	0.56	0.76	0.64	0.38
17	11.85	11.80	12.40	11.54	12.19	12.57	0.86	0.24	0.06	0.05	0.60
18	8.11	8.12	8.13	8.26	8.43	8.83	0.98	0.57	0.51	0.01	0.06
19	7.38	6.98	7.66	7.66	7.41	8.15	0.20	0.03	0.99	0.01	0.01
20	7.24	7.98	7.96	8.16	7.94	7.66	0.03	0.02	0.47	0.30	0.47
21	10.97	10.68	11.47	11.52	11.04	11.20	0.59	0.08	0.93	0.43	0.76
22	7.61	7.59	7.83	8.16	7.85	8.52	0.86	0.22	0.48	0.08	0.17
23	7.11	7.81	8.24	8.13	7.83	8.07	0.25	0.10	0.86	0.26	0.69
24	6.44	6.69	6.78	7.04	6.84	7.57	0.63	0.36	0.64	0.10	0.18
25	5.43	5.87	6.30	5.54	6.15	6.69	0.43	0.50	0.19	0.06	0.34
26	9.26	9.30	9.66	9.38	8.92	9.26	0.91	0.40	0.48	0.51	0.39
Means	8.56	8.65	9.03	8.91	8.89	9.19	0.72	0.01	0.24	0.01	0.02

† B0, absolute control; D0, control with a coulter-knife pass; PB, broadcast P; PD, deep-band P; KB, broadcast K; KD, deep-band K. All are means of two fertilization rates.
‡ CONT, comparison of the B0 and D0 controls; FERT, comparison of the controls vs. the fertilized treatments; PLACE, placement effects. Differences between P or K rates and the interaction rate vs. placement were nonsignificant ($P \leq 0.05$) at all sites.

observed even in soils with high stratification. The lack of yield response to P placement is in contrast to field observations (not shown) that planter-banded placement enhanced early growth of corn at some sites relative to other placements. The lack of grain yield response at sites with P_{ST} optimum or above coincides with published results (Mallarino and Blackmer, 1992; Webb et al., 1992) for fields managed with chisel-plow or ridge tillage and broadcast fertilization. The results for P suggest that P_{ST} stratification, P placement methods, and sampling depth for P are not major issues for no-till Iowa soils similar to those included in this study.

In contrast to results for P, there were small but frequent significant responses to K fertilization in soils that tested optimum or above in K_{ST}. Although analyses for each site showed statistically higher yields for deep-banded K at only two sites, yields for this placement were higher at many sites, and differences over all sites of both sets of trials were statistically significant. In most instances, however, the yield differences would not offset higher application costs. It is noteworthy that trends observed for the two trials (Sites 25 and 26) that evaluated residual treatment effects were similar to other trials.

The lack of sites with low K_{ST} and the small yield responses to K precludes a significant correlation study across sites. Relative yield responses to deep-banded K and K_{ST} at various depths across all sites were not significantly correlated, however. Moreover, the sites in which the response to K placement was largest did not always have the largest K_{ST} stratification. Although the K_{ST} stratification in these soils was less than for P, in average the soils had 40% higher K_{ST} in the 0- to 7.5-cm depth than in the 7.5- to 15-cm depth, and fields with long histories of no-till management had higher stratification.

It is likely that the responses to deep-banded K were related with weather conditions, particularly soil moisture. Rainfall early in the growing season was significantly ($P \leq 0.05$) correlated with yield response to K placement (soil moisture was not measured). The yield response to deep-banded K relative to the response to broadcast K increased ($r = 0.55$) with increasing May rainfall and decreased ($r = -0.44$) with increasing June rainfall (amounts of May and June rainfall are shown in Table 1). Yields of nonfertilized plots were negatively correlated with May rainfall ($r = -0.49$) and positively correlated with June rainfall ($r = 0.48$), which suggests that May rainfall sometimes was excessive for corn growth and that June rainfall sometimes was deficient. Yields or the effect of the K placement on yields were not correlated with any other monthly rainfall or air temperature and planting date. These correlations provide no proof of a cause–effect relationship, especially since May and June rainfall were negatively correlated ($r = -0.61$). The correlations do suggest, however, that response to deep-banded K was greater when there was little rainfall in June. Although there were no detailed evaluations of corn growth over time, the average growth stage in mid-June ranged from V4 to V10 (number of leaves with a visible collar) among sites. It is likely that plant K uptake from shallow soil layers was reduced by dry conditions during this growth period and that deep-banded K alleviated the problem.

Several factors could explain the more frequent and greater response of corn to deep placement of K (small response) compared with deep placement of P (no response). One likely explanation is the much larger K uptake by corn. Mackay et al. (1987), using the Claassen–Barber (1976) mechanistic model, reported that the proportion of total plant K uptake 30 to 77 d after planting derived from the 0- to 7.5-cm soil depth was 52% for no-till corn, but only 26% for conventionally tilled corn. Corresponding values for P uptake derived from the shallow depth were 39% for no-till corn (less than for K uptake) and 28% for conventionally tilled corn (similar to K uptake). Thus, K uptake from shallow soil depths could be more affected by moisture deficits than P uptake during periods of rapid early growth. This possibility agrees with observations in our study, in which responses to K placement were more related to low rainfall and unrelated to K_{ST}.

The lack of significant yield differences observed between the absolute control and the control that received a coulter–knife pass (sometimes referred to as strip tillage) shows that responses to deep-banded K were not due to the physical effects of the coulter and knife pass. Although planting on top of the tilled residue-free strip often enhanced early vegetative growth (data not shown), this effect almost never translated into higher grain yields.

Although crop responses to shallow or deep subsurface banding may not always result in large economic advantages for no-till producers, a decrease in nutrient contamination of surface water supplies is a potential benefit. Subsurface placements will reduce P accumulation at or near the soil surface in no-till fields and are likely to reduce P losses with water runoff. Research with various cropping systems (Sharpley and Menzel, 1987) has shown that conservation tillage systems often reduce total P losses to surface water supplies, but losses of soluble P are proportionally higher for these systems.

CONCLUSIONS

The results showed that P fertilization increased corn grain yields in several soils testing very low or low, and that there were no differences among P placements. Any of the placements evaluated are effective to alleviate P deficiencies in low-testing soils. The results indicate that recommended soil-test P interpretations and P fertilizer rates based on chisel-plow tillage also are appropriate for these no-till Iowa soils.

Potassium fertilization increased grain yields slightly in several soils that tested optimum or higher in K_{ST}. The responses were slightly higher for deep-band placement and seemed more related with deficient rainfall in late spring and early summer than with K_{ST}. High rates of broadcast K did not offset the advantage of deep-banded K. The results suggest that further work is needed to better characterize and predict no-till corn responses to deep-banded K. Because the observed yield responses usually were small, however, the cost-effectiveness of this placement compared with broadcast and planter-band placements will be determined largely by differences in the costs of application.

REFERENCES

Barber, S.A. 1971. Effect of tillage practice on corn (*Zea mays* L.) root distribution and morphology. Agron J. 63:724–726.

Belcher, C.R., and J.L. Ragland. 1972. Phosphorus absorption by sod-planted corn (*Zea mays* L.) from surface applied phosphorus. Agron. J. 64:754–757.

Claassen, N., and S.A. Barber. 1976. Simulation model for nutrient uptake from soil by a growing plant root system. Agron. J. 68:961–964.

Conservation Technology Information Center. 1996. National crop residue management survey. CTIC, West Lafayette, IN.

Eckert, D.J., and J.W. Johnson. 1985. Phosphorus fertilization in no-tillage corn production. Agron. J. 77:789:792.

Farber, B.G., and P.E. Fixen. 1986. Phosphorus response of late planted corn in three tillage systems. J. Fert. Issues 3:46–51.

Griffith, D.R., J.V. Mannering, and W.C. Moldenhauer. 1977. Conservation tillage in the eastern corn belt. J. Soil Water Conserv. 32:22–28.

Guertal, E.A., D.J. Eckert, S.J. Traina, and T.J. Logan. 1991. Differential phosphorus retention in soil profiles under no-till crop production. Soil Sci. Soc. Am. J. 55:410–413.

Karathanasis, A.D., and K.L. Wells. 1990. Conservation tillage effects on the potassium status of some Kentucky soils. Soil Sci. Soc. Am. J. 54:800–806.

Karlen, D.L., E.C. Berry, T.S. Colvin, and R.S. Kanwar. 1991. Twelve-year tillage and crop rotation effects on yields and soil chemical properties in northeast Iowa. Commun. Soil Sci. Plant Anal. 22:1985–2003.

Ketchenson, W.J. 1980. Effect of tillage on fertilizer requirements for corn on a silt loam soil. Agron. J. 72:540–542.

Mackay, A.D., E.J. Kladivko, S.A. Barber, and D.R. Griffith. 1987. Phosphorus and potassium uptake by corn in conservation tillage systems. Soil Sci. Soc. Am. J. 51:970–974.

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.

Mengel, D.B., S.E. Hawkins, and P. Walker. 1988. Phosphorus and potassium placement for no-till and spring plowed corn. J. Fert. Issues 5:31–36.

Moschler, W.W., and D.C. Martens. 1975. Nitrogen, phosphorus and potassium requirements in no-tillage and conventionally tilled corn. Soil Sci. Am. Proc. 39:886–891.

North Dakota Agric. Exp. Stn. 1988. Recommended chemical soil tests procedures for the North Central region. Rev. ed. North Central Regional Publ. 221.

Randall, G.W., and R.G. Hoeft. 1988. Placement methods for improved efficiency of P and K fertilizers: A review. J. Prod. Agric. 1:70–78.

Rehm, G.W. 1986. Effect of phosphorus placement on early growth, yield and phosphorus absorption by irrigated corn. J. Fert. Issues 3:12–17.

Sharpley, A.N., and R.G. Menzel. 1987. The impact of soil and fertilizer phosphorus on the environment. Adv. Agron. 41:297–324.

Shear, G.M., and W.W. Moschler. 1969. Continuous corn by the no-tillage and conventional tillage method: A six-year comparison. Agron. J. 61:524–526.

Singh, T.A., G.W. Thomas, W.W. Moschler, and D.C. Martens. 1966. Phosphorus uptake by corn (*Zea mays* L.) under no-tillage and conventional practices. Agron. J. 58:147–149.

Timmons, D.R., D.C. Erbach, R.M. Cruse, and T.S. Colvin. 1984. Fertility management for conservation tillage system. p. 20. *In* North West Res. Cent. Annual. Prog. Rep. 1983. Iowa State Univ., Ames, IA.

Voss, R.D., A.P. Mallarino, and R. Killorn. 1996. General guide for crop nutrient recommendations in Iowa. Iowa State. Univ. Ext. Publ. Pm-1688.

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.

Yibirin, H., J.W. Johnson, and D.J. Eckert. 1993. No-till corn production as affected by mulch, potassium placement, and soil exchangeable potassium. Agron. J. 85:639–644.

Nondestructive Estimation of Shoot Nitrogen in Different Rice Genotypes

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ABSTRACT

Plant N uptake and grain yield are important components of N use efficiency. Grain yield is easily measured, but plant N analysis is time consuming and requires hazardous chemicals or expensive equipment. A nondestructive method involving the least equipment and skill, to determine N uptake, is needed in agronomic and plant breeding experiments. A nondestructive method to determine shoot (aboveground biomass) N of transplanted rice (*Oryza sativa* L.) was developed based on SPAD-502 chlorophyll meter readings, leaf area, and tiller number. In two dry-season and one wet-season field experiment, shoot N of various genotypes at flowering were highly correlated ($P < 0.05$) with CLAT, the product of SPAD reading from a selected leaf (C), area of that leaf (LA), and number of tillers (T) ($r^2 = 0.46$, 0.90, and 0.85 in Exp. 1, 2, and 3, respectively); and with LAT, the product of LA and T ($r^2 = 0.56$, 0.88, and 0.76). Shoot N may be estimated using LAT for larger differences in leaf area compared with SPAD readings. Lower correlations in Exp. 1 were due to the lower range in shoot N contents. The highest correlation between shoot N and CLAT was observed in the third uppermost leaf. Regressions of shoot N on LAT and CLAT varied across growth stages and seasons. Thus, LAT or CLAT can be used to evaluate N uptake among N fertilizer treatments and different rice genotypes at a given stage within a season. Further work is needed to assess the reliability of this method under different seasons and cultural practices.

The SPAD-502 chlorophyll meter determines the relative amount of chlorophyll in leaves by measuring transmittances at red (650 nm, where absorption is high) and near-infrared (940 nm, where absorption is extremely low) wavelength regions (Minolta, 1989). The light transmitted by the leaf is converted into electrical signals, and the ratio of the intensities of the transmitted light at the two wavelength regions corresponds to the SPAD reading. Researchers have widely used SPAD

Abbreviations: C, SPAD chlorophyll meter reading; CLAT, SPAD reading × leaf area × tiller number; $CLAT_{1-4}$, CLAT averaged over the four uppermost leaves; CLA_2T and CLA_3T, CLAT measured from the second or third uppermost leaf; LA, leaf area; LAT, leaf area × tiller number; LAT_{1-4}, LAT averaged over the four uppermost leaves; LA_2T and LA_3T, LAT measured from the second or third uppermost leaf; LN/SN, ratio of leaf N to total shoot N; T, tiller number per plant.

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