Comparison of Methods for Determining Critical Concentrations of Soil Test Phosphorus for Corn

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ABSTRACT

Critical concentrations of soil-test P (STP) are used to identify soils where response to P fertilization should be expected. There is, however, little agreement concerning the methods that should be used to identify critical STP concentrations. This study compares the efficacy of critical STP concentrations generated by using various methods. Twenty-five P fertilization trials with corn (*Zea mays* L.) were established in Iowa. Available soil P at each site was estimated by the Bray-P_1, Mehlich-3, and Olsen extractants. Corn yield response was expressed in both absolute and relative terms and then related to STP values by using various statistical models (Cate-Nelson split, linear-plateau and quadratic-plateau segmented polynomials, the quadratic polynomial, an exponential Mitscherlich-type equation, and a multivariate polynomial). The use of various combinations of the extractants, expressions of yield response, and models resulted in a wide variety of critical STP concentrations. Comparisons of the ability of each critical concentration to generate economic returns when used to guide fertilization across the 25 sites showed that selection of the model was much more important than selection of the extractant or the expression of yield response. The best model was the Cate-Nelson, which identified critical concentrations of 13 mg kg^{-1} for the Bray-P_1, 12 mg kg^{-1} for the Mehlich-3, and 5 mg kg^{-1} for the Olsen extractants. Overall, the results of this study demonstrate that selection of the most appropriate critical STP concentration can be a major factor affecting the profitability of fertilization in areas having an abundance of soils testing high in P.

CRITICAL CONCENTRATIONS of STP are generally considered the soil test values below which crop responses to P fertilization should be expected and above which crop responses should not be expected. Critical concentrations of STP are known to vary with plant species, major differences in soil or climatic factors, and the analytical extractants used. The determination of an appropriate critical concentration of STP for a specific extractant and soil-plant category is a fundamental step required for use of soil testing in making fertilizer recommendations. Errors in determination of critical concentrations result in incorrect decisions relating to fertilizer applications.

Numerous models have been proposed for determining appropriate critical STP concentrations. These models describe an observed relationship between amounts of STP and some measurement of plant response to added P. Most commonly used models relate STP values to relative yields (i.e., yields without fertilizer expressed as percentages of maximum yield with fertilizer under otherwise similar conditions) or absolute yield increases (Nelson and Anderson, 1977; Evans, 1987). These relationships are usually described and analyzed by fitting continuous models (Nelson and Anderson, 1977; Peaslee, 1978), segmented polynomial models (Waugh et al., 1973), or by data-splitting models (Cate and Nelson, 1971). Other techniques involve incorporation of STP values into fertilizer response models (Bray, 1936; Colwell, 1967; Mombiela et al., 1981) or the use of multivariate polynomial models that include various controlled and uncontrolled variables in addition to STP values and fertilization treatments (Nelson, 1987).

The use relative yields as an expression of yield response in continuous models relating crop response with soil test values has been criticized for statistical reasons (Nelson and Anderson, 1977; Colwell et al., 1988). Also, it has been shown (Mombiela et al.,

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Abbreviation: STP, soil-test P.

1981; Dahnke and Olson, 1990) that the statistical model used to relate yield response with soil test values greatly influences the rates of fertilization that are recommended. There are, however, no published reports comparing the efficacy of alternative critical STP concentrations that were generated by using various combinations of extractants, expressions of yield response, and statistical models. Indeed, there is a lack of discussion about practical methods that could be used to make such comparisons.

The objective of this study was to compare the efficacy of various methods for determining critical STP concentrations for corn. Soil-test P was determined by three commonly used STP extractants to learn more about the relative importance of selecting extractants, expressions of yield response, and statistical models when determining critical STP concentrations. It seemed essential to include many high-testing soils in this study because reports (Killorn et al., 1990; Horstein et al., 1991) indicate that approximately 70% of the soil samples collected recently from Iowa fields tested high or very high in P (above 20 mg kg^{-1} by the Bray-P_1 extractant). Amid an abundance of high-testing soils, the efficacy of a soil test would be largely determined by its ability to correctly identify nonresponsive soils.

MATERIALS AND METHODS

Twenty-five P fertilization trials with corn were conducted in Iowa during 1989 and 1990. Each trial included treatments of 0, 25, 50, and 75 kg P ha^{-1} as broadcast triple superphosphate. The plots had a length of 12 m and a width of six rows (row width ranged from 76 to 97 cm among sites). Treatments were arranged in completely randomized designs having three replications. Analyses of variance were performed for yield data from each site and for all sites combined. A test of significance for the treatment-by-site interaction of the combined analysis was performed as outlined by Cochran and Cox (1957) for situations with heterogeneous variance among sites.

All trials were on farmers' fields, and soil and crop management practices (except N, P, and K fertilization) were those normally used by each farmer. Table 1 shows information about locations, soils, rainfall, and management practices. Corn was planted between 20 April and 13 May except at Site 22, where corn was replanted on 13 June because of herbicide damage. Nonlimiting rates of N and K fertilizers were applied at all sites. All fertilizers were broadcast in spring and incorporated by disking or chisel plowing except at sites managed with ridge tillage, where fertilizers were incorporated by the sweep of the planter during the ridge-cleaning operation. Corn grain was harvested from 7.6-m sections of two center rows and yields were adjusted to 155 g kg^{-1} moisture.

Soil samples were collected in spring from depths of 0 to 15 cm and 30 to 60 cm before applying the P treatments. Each sample was a composite of 25 cores (2.25-cm diam.) collected randomly from the experimental area except at sites managed with ridge tillage. At sites with ridge tillage, each composite sample was obtained by randomly collecting 15 cores from the top of the ridges, 15 cores from the shoulders, and 15 cores from the inter-ridge areas. All samples were air-dried and crushed to pass a 2-mm sieve. Analyses performed on surface samples included pH, organic

Table 1. Information describing soils, management practices, and rainfall at the sites included in the study.

			Soils						Soil P#					
Site	Year	Location	Series	Classification	H†	HYB‡	D§	R¶	B1	M3	OL	SUB	OC††	pH‡‡
								mm	—	mg kg^{-1}	—		g kg^{-1}	
1	1989	Shell Rock	Ostrander	fine-loamy, mixed, mesic, Typic Hapludoll	SD,S	D-572	4.88	271	7	6	4	4	18	6.2
2	1989	Audubon	Marshall	fine-silty, mixed, mesic, Typic Hapludoll	SC,S	W-1640	4.22	453	9	10	5	2	13	7.5
3	1989	Harpers Ferry	Downs	fine-silty, mixed, mesic, Mollic Hapludalf	FC,C	S-4103	4.39	483	13	12	5	21	17	7.0
4	1989	Eldora	Muscatine	fine-silty, mixed, mesic, Aquic Hapludoll	SD,S	N-4545	5.90	283	17	18	6	6	28	6.1
5	1989	Iowa City	Mahaska	fine, montmorillonitic, mesic, Aquic Argiudoll	FC,C	P-3379	5.20	445	20	19	8	7	19	6.5
6	1989	Ida Grove	Marshall	fine-silty, mixed, mesic, Typic Hapludoll	FC,C	P-3475	6.03	340	21	23	7	8	20	5.1
7	1989	Callender	Webster	fine-loamy, mixed, mesic, Typic Haplaquoll	RT,S	P-3475	5.74	486	20	24	10	1	31	7.4
8	1989	Holstein	Galva	fine-silty, mixed, mesic, Typic Hapludoll	SD,S	P-3475	5.29	251	27	27	10	7	27	5.8
9	1989	Holland	Tama	fine-silty, mixed, mesic, Typic Argiudoll	RT,S	F-SX212	6.13	264	25	29	16	3	44	6.4
10	1989	Monona	Fayette	fine-silty, mixed, mesic, Typic Hapludalf	SP,C	L-648	6.10	404	26	30	14	27	19	6.8
11	1989	Kensett	Canisteo	fine-loamy, mixed, calc., mesic, T. Haplaquoll	FC,S	P-3475	6.40	326	2	31	9	5	34	8.1
12	1989	Iowa City	Mahaska	fine, montmorillonitic, mesic, Aquic Argiudoll	SD,S	P-3379	5.44	445	26	31	15	5	24	6.8
13	1989	Wapello	Titus	fine, montm., mesic, Fluvaquentic Haplaquoll	FP,S	P-3377	4.91	373	36	37	18	4	24	6.7
14	1989	Hampton	Aredale	fine-loamy, mixed, mesic, Typic Hapludoll	RT,S	P-3585	4.73	281	38	41	15	8	24	5.9
15	1989	Badger	Webster	fine-loamy, mixed, mesic, Typic Haplaquoll	SD,S	P-3475	5.46	439	42	45	24	7	32	6.5
16	1989	Audubon	Marshall	fine-silty, mixed, mesic, Typic Hapludoll	RT,C	P-3377	4.17	453	42	49	16	10	18	6.2
17	1989	Boone	Webster	fine-loamy, mixed, mesic, Typic Haplaquoll	RT,S	P-3379	5.41	363	59	80	31	16	38	7.2
18	1990	Shell Rock	Ostrander	fine-loamy, mixed, mesic, Typic Hapludoll	SC,C	D-584	5.36	861	5	5	3	4	18	6.2
19	1990	Shell Rock	Ostrander	fine-loamy, mixed, mesic, Typic Hapludoll	SC,C	D-584	5.75	861	12	11	5	7	20	6.2
20	1990	Eldora	Muscatine	fine-silty, mixed, mesic, Aquic Hapludoll	SD,S	N-4545	5.80	895	14	14	6	6	27	6.1
21	1990	Fort Dodge	Clarion	fine-loamy, mixed, mesic, Typic Hapludoll	RT,S	C-488	5.32	884	15	14	7	2	20	6.3
22	1990	Hampton	Dinsdale	fine-silty, mixed, mesic, Typic Argiudoll	RT,S	P-3794	6.42	742	16	15	7	8	25	6.2
23	1990	Audubon	Marshall	fine-silty, mixed, mesic, Typic Hapludoll	SC,C	W-1700	3.77	631	22	26	12	7	17	6.7
24	1990	Holland	Tama	fine-silty, mixed, mesic, Typic Argiudoll	RT,S	F-5230	6.25	978	28	29	11	7	25	6.2
25	1990	Audubon	Marshall	fine-silty, mixed, mesic, Typic Hapludoll	RT,C	P-3379	4.78	616	49	56	24	10	18	6.2

† H = Primary tillage and previous crop: SD = spring disk or field cultivator, SP = spring moldboard plow, FP = fall moldboard plow, SC = spring chisel, FC = fall chisel, RT = ridge tillage, C = corn, S = soybean.

‡ HYB = Hybrid: C = Crow, D = Dekalb, F = Fontanelle, L = Land O' Lakes, N = Northrup King, P = Pioneer, S = Circle Seed, and W = Wilson.

§ D = Plant population (plants m^{-2}).

¶ R = rainfall from April to August.

Soil P (0 to 15 cm) determined by three extractants: B1 = Bray-P_1, M3 = Mehlich-3, and OL = Olsen; SUB = subsoil P (30 to 60 cm) determined by the Bray-P_1 extractant.

†† OC = Soil organic C (0 to 15 cm).

‡‡ Soil pH (0 to 15 cm).

Table 2. Effects of P fertilization on corn grain yields at 25 sites.†

Site	Grain yields with various P treatments‡				
	0	25	50	75	SE§
	Mg ha⁻¹				
1	4.33	5.92	4.71	5.86	0.42*
2	7.98	9.21	10.27	9.79	0.38*
3	9.01	10.17	9.77	9.97	0.21*
4	9.11	9.49	9.41	9.65	0.41
5	8.26	8.13	8.24	9.14	0.32
6	9.68	9.88	9.80	9.76	0.39
7	11.64	11.18	11.63	11.38	0.46
8	10.91	10.89	11.15	11.27	0.41
9	11.03	10.92	10.89	10.69	0.47
10	9.71	10.05	10.78	10.23	0.39
11	11.00	11.63	11.22	11.94	0.37
12	10.20	9.37	10.03	10.17	0.32
13	4.72	5.28	5.84	4.93	0.60
14	6.39	6.24	6.85	6.70	0.31
15	11.79	12.42	11.97	12.39	0.27
16	10.09	11.58	11.35	10.95	0.51
17	11.11	10.77	10.74	11.31	0.52
18	8.39	9.60	9.30	10.20	0.34*
19	7.96	8.67	8.86	8.44	0.40
20	8.41	8.29	7.79	7.87	0.37
21	9.02	8.82	9.14	8.61	0.32
22	6.45	6.61	6.53	7.02	0.10*
23	7.50	7.98	7.51	7.55	0.27
24	8.65	9.49	9.17	8.99	0.19*
25	10.54	10.42	10.98	10.64	0.29
Mean¶	8.96	9.32	9.36	9.41	0.30*

* Significant treatment effects, $P \leq 0.05$.
† Sites described in Table 1.
‡ P treatments of 0, 25, 50, and 75 kg P ha⁻¹.
§ Standard error of a treatment mean.
¶ The treatment-by-site interaction was significant at $P \leq 0.03$.

Table 3. Estimated net economic returns to P fertilization at 25 sites.†

Site	Net returns to P fertilization‡		
	25	50	75
	$ ha⁻¹		
1	118.30	−28.77	54.14
2	84.00	157.16	81.58
3	77.32	8.42	−1.26
4	1.12	−36.55	−42.50
5	−48.54	−66.81	−8.87
6	−16.50	−53.49	−86.56
7	−80.71	−66.12	−119.90
8	−36.85	−41.63	−59.67
9	−46.37	−78.11	−127.57
10	−2.51	38.68	−44.44
11	−116.38	−81.58	−97.02
12	25.58	−44.35	−3.82
13	18.42	42.96	−74.96
14	−50.71	−20.41	−64.66
15	25.55	−48.08	−36.08
16	108.62	56.66	−11.69
17	−68.69	−100.69	−74.80
18	82.18	23.16	80.77
19	33.42	22.03	−47.62
20	−54.79	−53.30	−134.09
21	−46.47	−124.93	−146.56
22	−20.29	−56.86	−39.19
23	10.19	−64.63	−90.25
24	45.09	−15.36	−62.13
25	−47.08	−22.68	−85.33
Mean	−0.24	−26.21	−49.70

† Estimates are based on average prices in the U.S. as detailed in Materials and Methods.
‡ P treatments of 25, 50, and 75 kg P ha⁻¹.

C, and STP by the Bray-P_1, Olsen, and Mehlich-3 extractants. The only analysis performed on subsoil samples was for P by the Bray-P_1 extractant. Except for the Mehlich-3 extractant, all analyses were performed following suggested procedures for the North Central region (North Dakota Agric. Exp. Stn., 1980). The procedure used to determine STP by the Mehlich-3 extractant was that described by Mehlich (1984). Briefly, STP by the Bray-P_1 and Mehlich-3 extractants were determined by using a 1:10 (wt/vol) soil:solution ratio and an extraction time of 5 min, and STP by the Olsen extractant was determined using a 1:20 (wt/vol) soil:solution ratio and an extraction time of 30 min. All extractions were performed in duplicate.

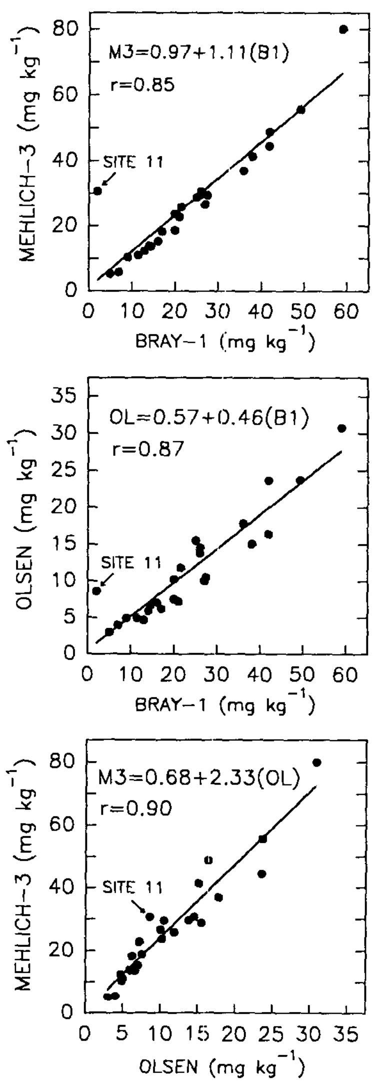

Fig. 1. Relationships between soil P extracted by the Bray-P_1 (Bl), Mehlich-3 (M3), and Olsen (OL) extractants across 25 sites.

Absolute yield increases due to fertilization were calculated by subtracting the mean yield of the nonfertilized plots from the mean yield of the fertilized plots for each site. Relative yields were defined as the mean yield of the nonfertilized plots expressed as percentages of the mean yield of fertilized plots for each site. Net economic returns to P fertilizer were calculated for each P treatment by subtracting the cost of fertilization from the value of additional grain produced. We used the mean price of triple superphosphate ($1.16 per kg of P) and grain ($0.09 per kg) in the USA from 1980 to 1989 (Agricultural Statistics Board, 1980-1989) and assumed a cost of application of $6.17 ha⁻¹.

Critical STP concentrations were determined for each extractant by various combinations of expressions of yield response (i.e., absolute yield increases or relative yields), statistical models, and sufficiency levels (i.e., percentages of the maximum predicted yield). The models used were the statistical Cate-Nelson split (Cate and Nelson, 1971), linear-plateau (Waugh et al., 1973) and quadratic-plateau (SAS Institute, 1988) segmented polynomials, the quadratic polynomial, an exponential equation [the Mitscherlich equation as expressed by Nelson and Anderson (1977)], and a multivariate polynomial. Critical STP concentrations are directly determined at a 100% sufficiency level when the Cate-Nelson or either segmented model is fitted to relative yields or absolute yield increases. The critical concentration for the Cate-Nelson model is the concentration that splits the data into two groups, and the critical concentration for either segmented model is the concentration at which the two portions of the model join. When the curvilinear models (including the quadratic-plateau) were fitted to relative yields, critical STP concentrations also were calculated by solving for the STP concentrations corresponding to sufficiency levels of 99, 95, and 90% of the maximum predicted yield by each model.

The multivariate models (one model for each extractant) were fitted to relationships between absolute yield increases and various site variables. The site variables were the linear and quadratic effects of STP, subsoil P, rainfall, plant population, and pH; the interactions of the linear and quadratic effects of STP with the linear effects of other variables; and all other simple linear interactions. These full models were reduced to models having only variables significant at $P \leq 0.10$ by using a backward elimination regression procedure (Draper and Smith, 1966; Laird and Cady, 1969). The rainfall index best related to yield response to P was selected by conducting various covariance analyses of rainfall and P fertilizer effects on yields. In each analysis, the covariable was the monthly rainfall between April and August or the sums of rainfall during two or more months. Because these analyses indicated that only rainfall during May had a significant ($P \leq 0.05$) effect on yield response, rainfall during May was included in the regression analyses. The multivariate models were further reduced to simple models relating yield increases and STP concentrations by substituting average observed values for the other site variables in the models and performing appropriate recalculations.

All statistical analyses were performed by using the general linear models (GLM), regression (REG), or nonlinear regression (NLIN) procedures of the SAS package (SAS Institute, 1988).

RESULTS AND DISCUSSION

The variety of growing conditions in this study resulted in grain yields that ranged from 5.2 to 12.1 Mg ha^{-1}. Timely rainfall was a major factor affecting crop growth during the 1989 growing season, which started with below-average amounts of soil moisture at most sites. Most sites had optimal to excess moisture throughout the 1990 growing season.

Phosphorus fertilization resulted in statistically significant yield increases at six of the 25 sites (Table 2). Application of 50 or 75 kg P ha^{-1} did not result in significant additional yield increases over the 25-kg rate at any site. A combined analysis of variance over sites revealed an overall positive effect of the 25-kg rate on corn yields, but a significant treatment-by-site interaction confirmed that yield responses differed among sites. Estimates of net economic returns to P fertilizer at prevailing fertilizer and grain prices (Table 3) illustrate that the profitability of P fertilization across the sites included in this study would largely depend on the ability of soil testing to identify soils where P fertilizer is not needed.

The three STP extractants tended to agree when evaluating the available P in one soil relative to that in other soils (Fig. 1). There was, however, one notable disagreement. The Mehlich-3 and Olsen extractants indicated more available P than did the Bray-P_1 extractant for the calcareous soil at Site 11. This finding is consistent with earlier reports (Olsen et al., 1954; Eik et al., 1961; Smith and Pesek, 1962; Wolf and Baker, 1985; Sen Tran et al., 1990) suggesting that the Bray-P_1 extractant often underestimates P availability in calcareous soils. The disagreements among extractants were small for other soils. Seemingly small disagreements, however, may be important for soils testing near critical STP concentrations because such disagreements provide a basis for comparing the reliability of the extractants for making fertilizer recommendations.

Multivariate regression analyses revealed that a high percentage (79% for the Bray-P_1, 71% for the Mehlich-3, and 82% for the Olsen extractants) of the variation in yield increases across sites was explained by models that included STP values and other variables listed in Table 4. These models indicate that yield increases due to P fertilization tended to decrease curvilinearly with increasing STP values. The effects of rainfall, plant population, subsoil P, soil pH, and (or) interactions of variables often were statistically significant and consideration of these effects helped ex-

Table 4. Multivariate regression models relating absolute yield increases with various variables across 25 sites.†

Extractant	Variable‡	Parameter estimate	Standard error	$P > t$
Bray-P_1	INTERCEPT	16.383	3.6848	0.001
	STP	−0.097	0.0186	0.001
	D	−4.561	1.3495	0.004
	STP^2	0.002	0.0005	0.001
	D^2	0.343	0.1254	0.015
	$SUBP^2$	0.004	0.0013	0.007
	STP × SUBP	−0.004	0.0016	0.035
	$R \times D$	0.074	0.0140	0.001
	$R \times$ pH	−0.070	0.0130	0.001
Mehlich-3	INTERCEPT	11.014	4.3470	0.022
	STP	−0.038	0.0151	0.022
	D	−3.817	1.5511	0.026
	pH	0.497	0.1713	0.010
	STP^2	0.001	0.0002	0.056
	D^2	0.265	0.1465	0.090
	$SUBP^2$	0.001	0.0005	0.065
	$R \times D$	0.083	0.0210	0.002
	$R \times$ pH	−0.079	0.0180	0.001
Olsen	INTERCEPT	10.769	5.0706	0.053
	STP	−0.150	0.0411	0.003
	R	0.850	0.0385	0.046
	D	−4.886	1.5865	0.009
	pH	0.922	0.2948	0.008
	STP^2	0.005	0.0014	0.006
	R^2	−0.006	0.0035	0.094
	D^2	0.387	0.1516	0.024
	$SUBP^2$	0.006	0.0026	0.046
	$R \times D$	0.076	0.0210	0.004
	$R \times$ pH	−0.185	0.0510	0.003
	$D \times$ SUBP	−0.025	0.0135	0.092

† The R^2 values for the models were 0.79 for the Bray-P_1, 0.71 for the Mehlich-3, and 0.82 for the Olsen extractants.

‡ Yield increases are expressed in kg ha^{-1}; STP = soil test P (mg kg^{-1}), D = plant population (plants m^{-2}), SUBP = subsoil P (Bray-P_1, mg kg^{-1}), and R = rainfall during May (cm).

Table 5. Statistical models used to determine critical concentrations of soil-test P for three extractants.

Response expression	Model†	Bray-P_1 Equation‡	R^2	$P > F$	Mehlich-3 Equation	R^2	$P > F$	Olsen Equation	R^2	$P > F$
Relative yields	CN	N/A#	0.47	0.001	N/A	0.53	0.001	N/A	0.53	0.001
	LP§	$82.0 + 0.99X$	0.30	0.005	$68.6 + 2.07X$	0.52	0.001	$61.2 + 6.11X$	0.46	0.001
	QP§	$82.6 + 1.21X - 0.025X^2$	0.26	0.030	$64.5 + 3.52X - 0.094X^2$	0.46	0.001	$52.4 + 11.6X - 0.753X^2$	0.40	0.003
	Q	$87.7 + 0.53X - 0.007X^2$	0.16	0.150	$88.2 + 0.39X - 0.004X^2$	0.16	0.140	$87.8 + 1.01X - 0.023X^2$	0.15	0.160
	EXP	$97.9 - 14.46e^{-0.103X}$	0.20	0.085	$97.4 - 53.32e^{-0.222X}$	0.42	0.002	$97.7 - 78.59e^{-0.527X}$	0.35	0.009
Yield increases	CN	N/A	0.48	0.001	N/A	0.50	0.001	N/A	0.50	0.001
	LP§	$1.53 - 0.08X$	0.31	0.004	$2.32 - 0.15X$	0.40	0.001	$3.05 - 0.47X$	0.41	0.001
	QP§	$1.51 - 0.11X + 0.0023X^2$	0.26	0.030	$2.56 - 0.24X + 0.0064X^2$	0.35	0.010	$3.90 - 0.95X + 0.0616X^2$	0.37	0.010
	Q	$1.05 - 0.05X + 0.0006X^2$	0.16	0.150	$0.92 - 0.03X + 0.0002X^2$	0.12	0.230	$1.04 - 0.08X + 0.0018X^2$	0.14	0.180
	EXP	$0.20 + 1.28e^{-0.1112X}$	0.21	0.077	$0.24 + 3.41e^{-0.1992X}$	0.31	0.016	$0.21 + 6.76e^{-0.541X}$	0.33	0.016
	M	$1.57 - 0.13X + 0.0022X^2$	0.79	0.001	$0.89 - 0.04X + 0.0004X^2$	0.71	0.004	$0.51 - 0.15X + 0.0049X^2$	0.82	0.003

† CN = Cate-Nelson, LP = linear-plateau, QP = quadratic-plateau, Q = quadratic, EXP = exponential, M = quadratic models that resulted from reducing the multivariate models shown in Tale 4 by substituting mean observed values for site variables other than soil-test P.
‡ X = soil-test P (mg kg^{-1}).
§ Equation shown applies for X values less than critical concentrations shown in Table 6 (values at which the two portions of the model join).
# N/A = not applicable.

plain much of the variation in yield increases across sites. Rainfall during May, the only monthly rainfall that affected yield response significantly, varied greatly over sites and years and ranged from 29 to 195 mm.

The statistical models shown in Table 5 were used to describe the observed relationships between STP concentrations and yield increases or relative yields shown in Fig. 2. The critical STP concentrations determined by using various combinations of extractants, expressions of yield response, models, and sufficiency levels are shown in Table 6. Comparisons of the various critical concentrations shown in this table reveal that statistical models and sufficiency levels had much greater effect on critical concentrations than did expressions of yield response. Clearly, determinations of critical STP concentrations were not influenced by the bias that may be introduced (Nelson and Anderson, 1977; Colwell et al., 1988) when transforming yields into relative yields.

The variety of critical concentrations shown in Table 6 illustrates an obvious need for having objective methods for evaluating critical concentrations. We reasoned that critical concentrations can best be evaluated through comparisons of their ability to generate

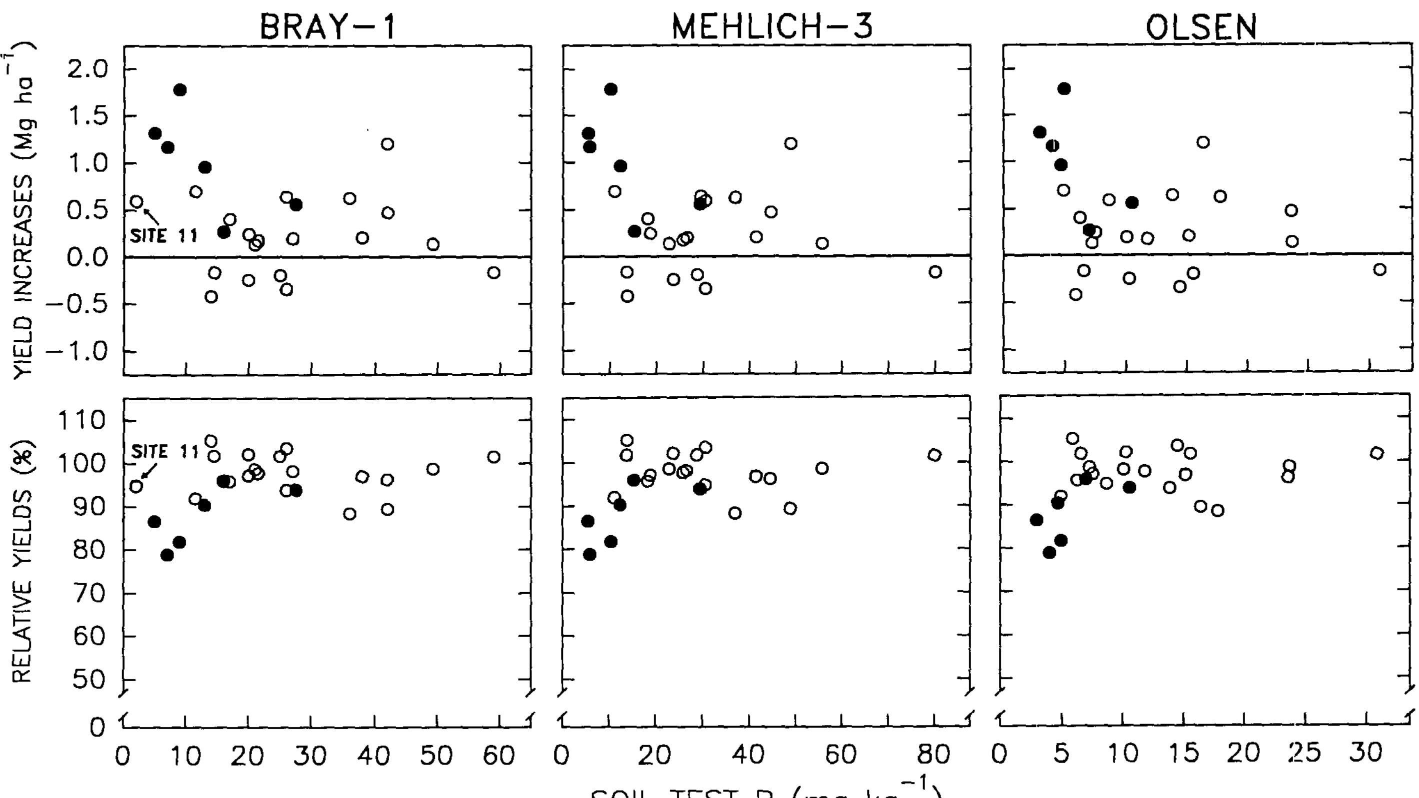

Fig. 2. Relationships between soil P extracted by three soil test extractants and absolute yield increases or relative yields. Solid symbols indicate sites where treatment effects on yields were statistically significant.

Table 6. Critical concentrations of soil-test P determined by using various extractants, expressions of yield response, models, and sufficiency levels.

Response expression	Model†	Sufficiency level	Critical concentrations		
			Bray-P_1	Mehlich-3	Olsen
		%	mg kg^{-1}		
Relative yields	CN	100	13	12	5
	LP	100	15	14	6
	QP	100	24	18	8
	QP	99	18	15	7
	QP	95	10	11	5
	QP	90	4	8	4
	EXP	99	26	18	8
	EXP	95	11	11	5
	EXP	90	4	8	4
Yield increases	CN	100	13	12	5
	LP	100	15	14	6
	QP	100	20	19	8
	M	100	31	48	15

† Models were defined in a footnote to Table 5; data for the quadratic model are not presented because this model was not significant for any extractant.

economic benefits when these critical concentrations are used to decide if P fertilizer should be applied. The results of such comparisons are presented in Table 7, which shows expected net economic returns to fertilization if each critical concentration were used to direct fertilizer applications in a scenario involving 25 fields (each 1 ha in size) corresponding to the sites included in this study. Comparisons of the estimated net returns reveal that selection of the model and the sufficiency level had much greater effect on the profitability of fertilization than did selection of the extractant. The Cate-Nelson model gave the highest net returns and the linear-plateau model usually gave the second highest. Neither of these models have a curvilinear component, and both essentially involve splitting soils into two categories based on the yield response to fertilization.

Our use of the net returns in Table 7 to evaluate critical STP concentrations tacitly defines critical concentrations in terms of probability of obtaining economic benefits rather than probability of obtaining yield increases. Defining a critical concentration in terms of economic benefits seems appropriate because economic benefits are the primary reason for applying fertilizers.

When yield responses were expressed in terms of relative yields, selection of a percentage sufficiency level for the curvilinear models greatly influenced critical STP concentrations and the resulting profitability of fertilization. For example, for the 25-kg P rate and the quadratic-plateau model with the Bray-P_1 extractant, net returns across the 25 fields ranged from $26 to $310 depending on the percentage sufficiency level selected. In this study, the 95% sufficiency level resulted in the highest returns for both the quadratic-plateau and exponential models. Although the concept of percentage sufficiency level is often associated with the use of relative yields in soil testing (Olson et al., 1987; Dahnke and Olson, 1990), our analyses show that arbitrary selection of percentage sufficiency levels is a questionable practice. Because direct economic analyses cannot be applied to relative yields (Nelson and Anderson, 1977; Evans, 1987), the problem of

Table 7. Effects of extractants, expressions of yield response, models, and sufficiency levels on net economic returns to P fertilizer in a scenario involving 25 fields corresponding to the 25 sites included in the study.†

Response expression	P rate	Model‡	Sufficiency level	Bray-P_1		Mehlich-3		Olsen	
				Returns	*N*§	Returns	*N*	Returns	*N*
	kg ha^{-1}		%	$		$		$	
Relative yields	25	CN	100	421	6	395	5	395	5
		LP	100	320	8	294	7	349	6
		QP	100	165	14	275	9	210	11
		QP	99	300	10	275	9	258	10
		QP	95	310	4	318	4	395	5
		QP	90	26	1	200	2	200	2
		EXP	99	0	17	106	14	210	11
		EXP	95	310	4	318	4	395	5
		EXP	90	26	1	200	2	200	2
	50	CN	100	138	6	182	5	182	5
		LP	100	−41	8	4	7	57	6
		QP	100	−385	14	−90	9	−210	11
		QP	99	−134	10	−90	9	−143	10
		QP	95	107	4	174	4	182	5
		QP	90	−44	1	−6	2	−6	2
		EXP	99	−506	17	−428	14	−210	11
		EXP	95	107	4	174	4	182	5
		EXP	90	−44	1	−6	2	−6	2
Yield increases	25	CN	100	421	6	395	5	395	5
		LP	100	320	8	294	7	349	6
		QP	100	175	12	226	10	210	11
		M	100	8	19	1	22	−43	20
	50	CN	100	138	6	182	5	182	5
		LP	100	−41	8	4	7	57	6
		QP	100	−267	12	−156	10	−210	11
		M	100	−563	19	−589	22	−583	20

† The scenario involved use of the critical concentrations shown in Table 6 to determine which sites should be fertilized and returns shown are the sum of the returns per ha (Table 3) for these sites.
‡ Models were defined in a footnote to Table 5; data for the quadratic model were not included because it was not significant.
§ *N* = number of sites fertilized in the assumed scenario.

selecting an optimal sufficiency level in advance has no straightforward solution even if crop and fertilizer prices are considered.

The net economic returns in Table 7 show that the multivariate model was not superior to the other models in ability to identify the most profitable critical STP concentration. The R^2 values and statistical significance for the multivariate models shown in Table 4 are irrelevant because weather and other site variables cannot be predicted accurately in advance of the season and, therefore, only averages for a region can be introduced into the models to identify critical concentrations. It is for this reason that significant variables other than STP listed in Table 4 are not directly shown in the simplified multivariate models in Table 5. The lack of superiority of the multivariate model may, in part, be caused by bias imposed by assumptions of only linear or quadratic relationships. The inadequacy of the quadratic model is obvious for the data collected in our study. Cerrato and Blackmer (1990) observed a similar problem when the quadratic model was used to identify optimum rates of fertilization. It is noteworthy that the best model in this study was the easiest to use. A plastic overlay having two intersecting lines (Cate and Nelson, 1971) superimposed on Fig. 2 would identify more profitable critical concentrations than did the complex multivariate analysis.

Overall, the results of this study show that commonly used methods disagree when identifying critical

STP concentrations for corn and that selection of the most appropriate critical concentration should be considered a major factor affecting the profitability of fertilization in areas having an abundance of high-testing soils. Decisions concerning selection of the extractant and the expression of yield response were unimportant compared to selection of a statistical model. The Cate-Nelson model was best under the conditions of this study, but research with other data is needed to determine which model is best for other conditions. It seems likely that objective evaluations of critical concentrations may resolve much of the controversy that has been associated (Eckert, 1987; Olson et al., 1987) with various philosophies of soil testing.

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