Response of Diverse Lettuce Types to Fertilizer Phosphorus

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Abstract. Four field experiments were conducted from 1990 to 1992 on Histosols in southern Florida to compare the relative response of various types of lettuce (*Lactuca sativa* L.) (i.e., leaf, Boston, Bibb, romaine, and crisphead lettuce) to P fertilization. All lettuce types showed large yield and quality responses to P fertilization. Because environmental conditions affected yield potential, P rates required for optimal yield varied for lettuce types across experiments. However, with the exception of Boston, the P rates required for optimal yield were similar when averaged over all experiments. Furthermore, the relationship between relative yield and soil-test P across all seasons showed that a similar soil-test P index level was required for maximum yield of all lettuce types. Overall, the results of this study suggest that existing soil-test-based fertilizer recommendations for crisphead lettuce are adequate for other lettuce types currently grown.

About 80,000 ha of lettuce is produced in the United States annually. Although most of this lettuce is the crisphead type, hectareage of other lettuce types has increased due to an expanding consumer demand. Leaf, butter, and romaine (cos) types are grown widely in the eastern and western United States. Of the butter types, Bibb and Boston are grown.

There is large variability in biomass production, morphological traits, and nutrient uptake by the various lettuce types. For example, leaf, Boston, Bibb, and romaine do not produce tight compact heads, as does crisphead lettuce. Additionally, leaf, Boston, and Bibb generally produce appreciably less biomass and, therefore, tend to accumulate lower amounts of nutrients than romaine and crisphead types.

The production of high-quality lettuce is highly dependent on soil fertility. Lettuce typically shows large yield and quality responses to fertilizer P (Alt, 1987; Greenwood et al., 1980; Sanchez et al., 1990). Phosphorus fertilizer recommendations for lettuce grown on organic soils in southern Florida are based on a water-extractable P soil test (Sanchez, 1990). However, these recommendations are based primarily on soil-test-calibration research conducted with the crisphead type. Limited infor-

mation is available for making P fertilizer recommendations for lettuce types other than crisphead. Our objective was to evaluate the relative response of five lettuce types to P fertilization.

Materials and Methods

Four field experiments were conducted from 1990 to 1992 in commercial lettuce fields across the Everglades agricultural area. We evaluated leaf, Bibb, Boston, romaine, and crisphead type lettuce; selected cultivars ap-

propriate for various planting dates; and recorded harvest dates and weather conditions (Table 1). Spring 1990 and Fall 1991 experiments were conducted on a Pahokee muck (euic hyperthermic Lithic Medisaprist); Fall 1990 and Winter 1991 experiments were conducted on a Terra Ceia muck (euic hyperthermic Typic Medisaprist). We selected sites that tested low in available P. Water-extractable P values before fertilization were (in g·m⁻³) 0.5 in Spring 1990, 4.0 in Fall 1990, 2.9 in Fall 1991, and 4.4 in Winter 1991. Soil on all sites was calcareous with pH values ranging from 6.7 to 7.3.

Phosphorus rates were 0, 50, 100, 200, and 300 kg P/ha in all experiments, using triple superphosphate. Each experiment used a split-plot arrangement in a randomized complete-block design with four replications in Spring 1990 and five replications in all other experiments. Phosphorus treatments were the main plots and lettuce types the subplots. The main plots measured 8.1 m wide (nine beds 0.9 m wide × 15.2 m long). The center five beds of the plot area contained the five lettuce types and were bordered on each side by two beds of crisphead lettuce.

All fertilization, other than P, were standard practices. The micronutrients Zn, Mn, and B were applied at 9, 9, and 2 kg·ha⁻¹, respectively. Potassium was applied as KCl based on preplant soil tests (Sanchez, 1990). Phosphorus, K, and micronutrients were broadcast-applied and disked into the soil before planting. Nitrogen was applied at 50 kg·ha⁻¹ as a sidedress at the eight-leaf stage. Water was supplied using subsurface irrigation by attempting to maintain a water table ≈60 cm below the soil surface (Snyder et al., 1978).

Lettuce was seeded in elevated double-row beds on 0.9-m centers and thinned at the four-leaf stage to a 25-cm intrarow spacing to give a plant population of ≈60,000 plants/ha. At maturity, heads of each lettuce type were har-

Table 1. Lettuce type, cultivar, planting date, harvest date, and weather conditions across P fertilizer field experiments.

Experiment	Lettuce		Date		Mean temp (°C)	Rainfall (mm) ²	Pan evaporation (mm) ²
	Type	Cultivar	Planting	Harvest			
Spring 1990	Leaf	Royal Green	28 Feb.	23 Apr.	20.8	44	278
	Bibb	Floribibb	28 Feb.	27 Apr.	20.9	44	305
	Boston	Genecorp Boston	28 Feb.	27 Apr.	20.9	44	305
	Romaine	Tall Guzman	28 Feb.	2 May	21.1	82	333
	Crisphead	South Bay	28 Feb.	2 May	21.1	82	333
Fall 1990	Leaf	Royal Green	29 Nov.	2 Feb.	20.2	241	192
	Bibb	Floribibb	29 Nov.	2 Feb.	20.2	241	192
	Boston	Genecorp Boston	29 Nov.	2 Feb.	20.2	241	192
	Romaine	Tall Guzman	29 Nov.	7 Feb.	20.2	241	212
	Crisphead	South Bay	29 Nov.	7 Feb.	20.2	241	212
Fall 1991	Leaf	Royal Green	15 Nov.	9 Jan.	19.1	68	153
	Bibb	Floribibb	15 Nov.	9 Jan.	19.1	68	153
	Boston	Genecorp Boston	15 Nov.	9 Jan.	19.1	68	153
	Romaine	Augustus	15 Nov.	15 Jan.	19.6	78	173
	Crisphead	Raleigh	15 Nov.	24 Jan.	18.9	89	193
Winter 1991	Leaf	Royal Green	3 Dec.	31 Jan.	17.6	40	155
	Bibb	Floribibb	3 Dec.	31 Jan.	17.6	40	155
	Boston	70291MT	3 Dec.	1 Feb.	17.6	40	160
	Romaine	Tall Guzman	3 Dec.	11 Feb.	17.4	76	190
	Crisphead	Raleigh	3 Dec.	11 Feb.	17.4	76	190

²Differences in pan evaporation, and sometimes rainfall, among lettuce types within season occurred because of different harvest date.

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vested from 6 m of each of two rows per bed. Marketable yields were determined after grading according to standard marketing criteria. In all experiments, lettuce plants were collected for P analysis from each plot at maturity. The oldest sound leaf from each of 10 plants was collected in each plot at the eight-leaf stage in Fall 1991 and Winter 1991. Plant material was dried at 60C for 48 h. After wet-ashing, P was determined colorimetrically (Wolf, 1982). Soil samples were taken at random within the lettuce beds to a depth of 15 cm $\approx$ 30 to 40 days after fertilizer application. These samples were analyzed for water-soluble P using Murphy and Riley's (1962) method after a 1 soil : 12.5 water (v/v) extraction (Sanchez, 1990). Because of weather conditions, we were not able to take soil samples during Spring 1990. The soil test information was used to estimate critical soil test values required for optimal yield of each lettuce type.

Data were subjected to analysis of variance using the SAS general linear model, and response models were evaluated using the SAS general linear model and SAS-Nonlinear routine (SAS Institute, 1982). Several models were evaluated, including the polynomial linear and quadratic, linear response and plateau, and quadratic response and plateau. Model selection was based on the coefficient of determination and a visual inspection of the residuals.

Results and Discussion

Marketable yields ranged from (in $\text{Mg}\cdot\text{ha}^{-1}$) 17.7 to 30.6 for leaf, 11.2 to 18.7 for Bibb, 7.4 to 18.7 for Boston, 23.5 to 47.6 for romaine, and 18.6 to 52.1 for crisphead lettuce. Although we selected cultivars considered appropriate for each season, there were strong environmental interactions with marketable yields of all lettuce types. Warm weather during the latter part of the growing season in Spring 1990 limited yields for crisphead lettuce. During Fall 1990, a 140-mm rainfall on 15 Jan. flooded the field for $\approx$ 24 h. This flooding of the root zone seemed to have the greatest negative impact on Boston, romaine, and crisphead lettuce types. Growing conditions encountered during Fall 1991 and Winter 1991 were generally favorable for the production of all lettuce types.

Applying P during all experiments significantly increased lettuce yield, tissue P concentration, and aboveground P accumulation (Tables 2–5). Because there were significant P rate $\times$ lettuce type interactions, yield response equations to P for each lettuce type were determined (Table 2). An illustration of the observed and predicted response among lettuce types is shown for Fall 1991 in Fig. 1.

Interestingly, the relative yield response of lettuce types to P varied by experiment (Table 2). For example, in Spring 1990 Bibb and crisphead showed a lesser response to P than did leaf, Boston, and romaine. However, Bibb and crisphead lettuce showed the greatest response to P in Fall 1990, but Bibb did in Fall 1991.

An evaluation of aboveground whole-plant

P concentration and P accumulation data in our experiments offers limited interpretive insight concerning the variable yield response (Tables 3 and 5; Fig. 2). Generally, leaf, Boston, Bibb, and romaine tended to have higher P concentrations in mature heads than crisphead

lettuce (Table 3). A notable exception was in Spring 1990, when crisphead performed poorly relative to the other lettuce types grown during the same period. Although P concentrations in the mature plants of leaf, Boston, Bibb, and romaine were generally higher than those of

Table 2. Summary of equation parameters for relationships between marketable yield and fertilizer P for the various lettuce types across four field experiments.

Experiment	Lettuce type	Model selected ^z	Equation parameters				P rate for max. yield ($\text{kg}\cdot\text{ha}^{-1}$)	Max. yield ($\text{Mg}\cdot\text{ha}^{-1}$)
			A	B	C	r^2		
Spring 1990	Leaf	Quad	15.49	0.089	-0.00013	0.83	300	30.6
	Bibb	QRP	13.00	0.154	-0.00104	0.46	74	18.7
	Boston	Quad	14.75	0.048	-0.00006	0.66	300	23.3
	Romaine	Quad	27.82	0.094	-0.00015	0.66	300	42.7
	Crisphead	QRP	19.84	0.297	-0.00131	0.65	113	36.7
Fall 1990	Leaf	QRP	9.96	0.085	-0.00026	0.46	160	16.7
	Bibb	Quad	8.19	0.054	-0.00014	0.52	195	12.5
	Boston	Quad	2.75	0.0122	0.00002	0.78	300	7.41
	Romaine	QRP	1.75	0.619	-0.00441	0.69	70	23.5
	Crisphead	Quad	4.47	0.053	-0.00002	0.75	300	18.6
Fall 1991	Leaf	QRP	10.50	0.339	-0.00401	0.75	42	17.7
	Bibb	QRP	5.31	0.088	-0.00033	0.69	133	11.2
	Boston	QRP	2.73	0.297	-0.00159	0.91	93	16.6
	Romaine	QRP	13.23	0.694	-0.00367	0.66	94	45.9
	Crisphead	QRP	27.53	0.639	-0.00415	0.73	77	52.1
Winter 1991	Leaf	QRP	4.42	0.355	-0.00195	0.74	91	20.6
	Bibb	QRP	2.28	0.146	-0.00044	0.83	165	14.4
	Boston	QRP	2.35	0.213	-0.00090	0.88	118	14.9
	Romaine	QRP	21.21	0.471	-0.0021	0.68	112	47.6
	Crisphead	QRP	2.63	0.884	-0.00451	0.91	98	46.0

^zQuad = polynomial quadratic ($Y = A + bx + Cx^2$); QRP = quadratic response and plateau model ($Y = A + Bx + Cx^2$ if $x < C_p$ or $Y = Y_p$ if $x \geq C_p$). Y is marketable yield (megatons per hectare), x is P rate (kilogram per hectare); A (intercept), B (linear coefficient), C (quadratic coefficient), C_p (critical rate of fertilization, which occurs at the intersection of the quadratic response and the plateau lines), and Y_p (plateau yield) are constants obtained by fitting the model to the data.

Table 3. Phosphorus concentration in aboveground whole plant at maturity for five lettuce types in four experiments.

P rate ($\text{kg}\cdot\text{ha}^{-1}$)	P concn ($\text{g}\cdot\text{kg}^{-1}$)				
	Lettuce type				
	Leaf	Bibb	Boston	Romaine	Crisphead
<i>Spring 1990</i>					
0	3.6	7.4	5.2	5.9	5.9
50	4.4	9.7	6.4	7.6	6.7
100	3.5	9.7	5.8	6.4	6.1
200	4.6	8.7	6.8	8.1	6.7
300	5.4	11.3	8.5	7.1	6.4
Statistic	L**	L*	L**	NS ^z	NS ^z
<i>Fall 1990</i>					
0	5.6	6.7	6.5	5.2	3.7
50	6.8	7.1	6.1	6.5	5.4
100	8.3	8.7	6.6	6.7	5.8
200	9.1	8.9	8.0	7.9	6.6
300	9.4	10.9	9.7	9.7	7.1
Statistic	L***, Q*	NS ^z	L***, Q*	L***	L***, Q*
<i>Fall 1991</i>					
0	6.7	6.7	7.0	4.6	5.3
50	8.6	7.9	8.9	6.8	6.8
100	9.6	9.0	9.9	6.6	7.1
200	9.7	9.2	10.6	7.9	7.5
300	10.8	10.0	11.1	7.9	8.3
Statistic	L***, Q*	L***, Q*	L***, Q***	L***, Q***	L***
<i>Winter 1991</i>					
0	7.7	7.0	7.5	8.0	5.4
50	9.2	8.5	9.5	9.9	8.4
100	10.2	9.4	9.9	11.2	8.6
200	11.0	10.4	11.8	11.5	9.6
300	12.1	10.7	12.7	13.7	10.3
Statistic	L***, Q*	L***, Q*	L***	L***	L***, Q*

^zNon-significant at $P > 0.1$.

***, **, *Significant linear (L) or quadratic (Q) trend at $P \leq 0.001$, 0.01, and 0.1, respectively.

Table 4. Leaf P concentration at the eight-leaf stage for five lettuce types as influenced by P rate during two growing seasons.

P rate (kg·ha ⁻¹)	P concn (g·kg ⁻¹)				
	Lettuce type				
	Leaf	Bibb	Boston	Romaine	Crisphead
<i>Fall 1991</i>					
0	6.7	5.2	4.9	4.7	3.4
50	8.7	5.7	6.0	6.1	4.7
100	8.9	6.9	6.2	7.2	5.1
200	9.4	7.3	6.9	7.6	5.1
300	9.9	8.1	7.2	8.3	5.6
Statistic	L ^{**} , Q ^{**}	L ^{**} , Q [*]	L ^{***} , Q ^{**}	L ^{***} , Q ^{***}	L ^{***} , Q [*]
<i>Winter 1991</i>					
0	6.8	5.2	7.6	4.6	4.4
50	8.6	7.0	8.5	6.3	6.8
100	9.5	7.2	9.5	7.7	7.0
200	10.0	8.8	10.1	8.2	7.6
300	10.7	8.7	10.4	8.9	8.6
Statistic	L ^{***} , Q ^{**}	L ^{***} , Q ^{**}	L ^{***} , Q ^{**}	L ^{***} , Q ^{***}	L ^{***} , Q [*]

***, **, *Significant linear (L) or quadratic (Q) trend at $P \leq 0.001$, 0.01, and 0.1, respectively.

^{ns}Nonsignificant at $P > 0.1$.

Fig. 1. Observed and predicted yield response of five lettuce types to P fertilization during Fall 1991.

Table 5. Regression equations describing aboveground P accumulation by five lettuce types across four seasons.

Experiment	Lettuce type	Equation parameters ^z			r^2
		A	B	C	
Spring 1990	Leaf	4.58	0.0252	---	0.80
	Bibb	4.84	0.0105	---	0.48
	Boston	3.31	0.0141	---	0.74
	Romaine	10.66	0.0220	---	0.75
	Crisphead	6.82	0.0154	---	0.32
Fall 1990	Leaf	2.53	0.0302	-0.00005	0.80
	Bibb	3.23	0.0831	---	0.60
	Boston	1.88	0.0110	---	0.84
	Romaine	4.09	0.0221	---	0.77
	Crisphead	3.68	0.0173	---	0.87
Fall 1991	Leaf	5.53	0.0379	-0.00008	0.57
	Bibb	3.53	0.0245	-0.00006	0.51
	Boston	4.10	0.0278	-0.00004	0.85
	Romaine	6.36	0.0861	-0.00019	0.85
	Crisphead	10.36	0.021	---	0.60
Winter 1991	Leaf	6.78	0.0540	-0.00011	0.77
	Bibb	4.09	0.0389	-0.00007	0.85
	Boston	4.75	0.04365	-0.00008	0.70
	Romaine	14.22	0.0339	---	0.64
	Crisphead	7.95	0.0759	-0.00014	0.79

^zQuadratic has the form $Y = A + Bx + Cx^2$ and linear has the form $Y = A + Bx$, where Y is total aboveground P (in kilograms per hectare); x is fertilizer rate (in kilogram per hectare); and A (intercept), B (linear coefficient), and C (quadratic coefficient) are constants obtained by fitting model to the data.

crisphead lettuce, romaine and crisphead lettuce consistently accumulated more P because of their larger biomass production (Table 5 and Fig. 2). Romaine and crisphead lettuce tended to accumulate more P than leaf, which, in turn, generally accumulated more P than Bibb and Boston.

Although differences in tissue P concentration among the lettuce types did not consistently explain the variability in P rates required for maximum yields, these differences might affect the values for critical tissue P concentration within each lettuce type (Tables 3 and 4). Because we collected leaf tissue data at the eight-leaf stage only in the Fall 1991 and the Winter 1991 experiments, we are not able to estimate critical leaf-P concentrations with confidence. However, as with the whole aboveground plant tissue at maturity, P concentrations in the leaf tissue at the eight-leaf stage were generally higher for leaf, Bibb, Boston, and romaine than for crisphead lettuce. Additional work to generate reliable critical P concentrations for lettuce types other than crisphead is needed.

Overall results from this study show the P rate $\times$ lettuce type interactions for most measured responses were strongly influenced by the performance of individual lettuce types within season. Similar results were observed in another study comparing the relative response of several crisphead cultivars to fertilizer P (Nagata et al., 1992). Because weather conditions in southern Florida during the fall-winter-spring period are not predictable, fertilizer recommendations should be based on long-term probability of response.

Averaging the data from all four experiments, mean P rates required for maximum yield on these low-P testing soils were (in kg P/ha) 148 for leaf, 142 for Bibb, 202 for Boston, 144 for romaine, and 147 for crisphead lettuce. Thus, with the exception of Boston, a similar average P rate was required for maximum yield of all lettuce types over all experiments. Furthermore, the relationship between relative yield and soil-test P across seasons (Table 6 and Fig. 3) showed that the estimated critical soil-test P level for leaf, Boston, romaine, and crisphead lettuce type were close to the 22 g·m⁻³ currently used to make P fertilizer recommendations for lettuce on Histosols in southern Florida. Although the calculated critical soil-test P level for Bibb lettuce appeared to be slightly higher, the data for Bibb were more variable (note the lower r^2 value), and the estimated critical soil-test P index also is within error of the critical concentration currently used.

The results of these experiments were somewhat surprising because crisphead and romaine lettuce generally produce appreciably more biomass and accumulate more P than the leaf, Boston, and Bibb types. One might expect the latter lettuce types to consistently have a lower P requirement. However, Buso and Bliss (1988), using sand culture techniques, suggested that some butterhead types were actually less P efficient than other lettuce types under P-deficient regimes. These authors, however, found no differences among

Fig. 2. Predicted P accumulation by five lettuce types during four cropping seasons. (—) Leaf; (---) Bibb, (.....) Boston, (- - - -) Romaine, and (— · — · —) crisphead.

Table 6. Equation parameters for relative yield of five lettuce types as influenced by soil-test P.

Lettuce type	Equation parameters ^a				Critical soil test P levels (g·m ⁻³)
	A	B	C	r ²	
Leaf	21.62	7.40	-0.183	0.56	20.2
Bibb	26.55	5.53	-0.105	0.46	26.2
Boston	-26.17	10.87	-0.234	0.83	23.2
Romaine	-4.34	9.88	-0.245	0.60	20.2
Crisphead	-39.18	13.53	-0.330	0.91	20.2

^aQuadratic response and plateau model has the form $Y = A + Bx + Cx^2$ if $x < C_p$ and $Y = Y_p$ if $x \geq C_p$, where Y is relative yield and x is soil-test P (in grams per cubic meter); A (intercept), B (linear coefficient), C (quadratic coefficient), C_p (critical soil test P level that occurs at intersection of the quadratic response and the plateau lines), and Y_p (plateau yield) are constants obtained by fitting model to the data.

Fig. 3. Relative yield of five lettuce types as influenced by soil test P.

lettuce types under conditions of high P and found no differences in P efficiency among butterhead types grown in two geographic regions. They suggested that the lack of differences observed under conditions of high P may be because most lettuce cultivars are typically bred and grown under conditions of high fertility.

Results of this study provide a basis for concluding that various lettuce types should be fertilized similarly in respect to P and suggest that current soil-test-based P fertilizer recommendations used for crisphead lettuce are generally adequate for other lettuce types grown.

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