Sugarcane Response to Phosphorus Fertilizer on Everglades Histosols

J. Mabry McCray,* Ronald W. Rice, Yigang Luo, and Shangning Ji

ABSTRACT

Determining sugarcane (*Saccharum* spp.) yield response to P fertilizer supports the development of agricultural best management practices consistent with Everglades restoration efforts. Field studies were conducted on organic soils to determine sugarcane yield responses to P fertilizer. Four test sites were established on Florida Histosols (water-extractable P = 1.3, 1.7, 2.1, and 9.0 g P m^{-3}) with annual banded rates of 0, 9, 18, 36, 72, and 144 kg P ha^{-1}. There were a total of 13 crop years with duration of each test ranging from 2 to 4 yr. Linear and quadratic regression and single degree of freedom contrasts were used to determine P fertilizer requirements. There were responses in t cane ha^{-1} (TCH) and t sucrose ha^{-1} (TSH) to P fertilizer application at four and three sites, respectively. Annual fertilizer P requirement at the four sites ranged from 18 to 33 kg P ha^{-1}, with no consistent change in P requirement across crop years. Based on measured response (95% of maximum yield) in TCH and TSH up to 33 kg P ha^{-1}, the maximum P recommendation for sugarcane grown on Florida Histosols should be maintained at 36 kg P ha^{-1}. Minimal reductions in sucrose concentration (kg sucrose t^{-1} cane) were measured at P rates ≤36 kg P ha^{-1}. Water-extractable P did not predict the measured yield response at all sites, demonstrating the need for an updated soil test calibration that should be applicable over a wide pH range and include both quickly available and reserve soil P.

Approximately 80% of the 157,000 ha of sugarcane in Florida is grown on organic soils in the Everglades Agricultural Area (EAA) (Rice et al., 2009). Use of P fertilizers in the EAA has been under public scrutiny because the EAA basin drains into the Everglades ecosystem and increased P concentrations have been found to accelerate eutrophication of these systems (Bottcher et al., 1995) resulting in changes in vegetation communities (Gaiser et al., 2005; Noe et al., 2002; Reddy et al., 1998). There is a legislative mandate through the Everglades Forever Act (Florida State Statutes, 1994) in Florida that requires reductions in P loads discharged in water from EAA farms. These reductions need to be at least 25% relative to historic baseline trends determined using subbasin P load data collected during 1978 to 1988 (Whalen and Whalen, 1994). This legislation also requires Florida sugarcane growers to use best management practices (BMPs) designed to reduce P loads in farm drainage (Rice et al., 2002). The BMP program has resulted in a long-term total P load reduction of 54%, with an estimated 68% load reduction in 2009 (Horn and Wade, 2009). Soil testing is an important BMP that growers use to meet the load reduction requirements (Daroub et al., 2005).

Water-extractable P is currently used by the Everglades Soil Testing Laboratory (University of Florida) to make P fertilizer recommendations for sugarcane (Gilbert and Rice, 2009). Phosphorus is recommended for plant cane, first ratoon, and second ratoon crops on soils with water-extractable P ≤ 4.4, 5.1, and 6.6 g m^{-3}, respectively (Gascho and Kidder, 1979). It is recommended that growers band P fertilizer to maximize its efficiency (Lang et al., 2006). The current maximum P fertilizer rate of 36 kg P ha^{-1} was determined by Gascho and Kidder (1979) and there were no sugarcane yield responses to rates exceeding that maximum in studies by Andreis and McCray (1998). Glaz et al. (2000a) measured yield responses in TCH and TSH between the 24 and 48 kg P ha^{-1} rates, but they did not have an intermediate rate to determine if there was a response beyond 36 kg P ha^{-1}. Coale et al. (1993) reported that P removed from Histosols by sugarcane harvest averaged 23 kg P ha^{-1} with a total accumulation in the crop of 38 kg P ha^{-1}. In that study, fertilizer P appeared to be a minor contributor to plant-available P, since sugarcane harvest removed an average of 179% of applied fertilizer P. Incubation studies by Reddy (1983) determined that soluble P was released in organic soils as organic matter decomposed, with typical P mineralization rates in the EAA of 16 to 23 kg P ha^{-1} yr^{-1}. Mineralization rates vary with soil wetness, with higher P release occurring under periodic flooding and draining compared with constantly drained conditions (Diaz et al., 1993).

The objective of this study was to determine sugarcane yield responses to P fertilizer rates at multiple organic soil locations in south Florida. This study was part of a larger effort to update the soil-test P calibration for sugarcane grown on Everglades Histosols. The evaluation of yield response in relation to soil-test P using multiple soil extractants will be reported separately.

J.M. McCray, Y. Luo, and S. Ji, Univ. of Florida, EREC, 3200 E. Palm Beach Rd., Belle Glade, FL 33430; R.W. Rice, Univ. of Florida/Palm Beach County Extension Service, 2976 State Rd. 15, Belle Glade, FL 33430. Received 2 Feb. 2010. *Corresponding author (jmmccray@ufl.edu).

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Abbreviations: BMP, best management practice; EAA, Everglades Agricultural Area; KST, sucrose concentration (kg sucrose t^{-1} cane); MAP, monoammonium phosphate; RCBD, randomized complete block design; TCH, t cane ha^{-1}; TSH, t sucrose ha^{-1}; TSP, triple superphosphate.

MATERIALS AND METHODS

Experimental Design

All test sites were in the EAA of southern Florida (Table 1). Site 1 was a Terra Ceia muck soil (euic, hyperthermic Typic Haplosaprist). Sites 2 and 4 were Pahokee muck soils (euic, hyperthermic Lithic Haplosaprist). Site 3 was a Dania muck soil (euic, hyperthermic, shallow Lithic Haplosaprist). All soils were organic with <35% mineral content. The soil series are differentiated largely by the depth of the organic soil profile to the underlying limestone bedrock, with the deeper Terra Ceia (>1.30 m), intermediate Pahokee (0.91–1.30 m), and shallower Dania (<0.51 m) (Rice et al., 2005).

All experimental designs were randomized complete block designs (RCBD) with six, eight, six, and five replications at Sites 1, 2, 3, and 4, respectively. The study was conducted at different sites in different calendar years, so site and calendar year were confounded (Table 1). Also, since different cultivars were grown at different sites, cultivar was confounded with site and calendar year in the study. Test Sites 1 to 3 were established at planting and Site 4 was established with the first ratoon crop. All plots were 13.2 m long with 1.5-m row spacing. Plots at Sites 1 and 2 were four rows wide and plots at Sites 3 and 4 were six rows wide. Plots at Sites 1 to 3 were separated by 3-m lengthwise alleys and 4.6-m cross alleys. Plots at Site 4 were separated by 6.1-m lengthwise alleys and 4.6-m cross alleys. All tests were planted vegetatively either by placing precut sugarcane billets (45–60 cm) in the furrows with two seed pieces side-by-side in the furrows throughout the plot length (Sites 1 and 2) or by placing pairs of whole sugarcane stalks side-by-side in the furrows and chopping them into similar billet lengths (Sites 3 and 4) to fill the plot length before closing the furrows.

Fertilizer Applications

Phosphorus rates applied to each crop of all four tests were 0, 9, 18, 36, 72, and 144 kg P ha^{-1} except that all plots at Site 4 received no P for the plant cane crop. Phosphorus rates were selected by multiplying the maximum University of Florida recommended P rate of 36 kg P ha^{-1} by 0.25, 0.5, 1, 2, and 4 to determine the above P rates. The 0 to 72 kg P ha^{-1} range was expected to encompass all positive yield responses to P fertilizer. The 144 kg P ha^{-1} rate was included to investigate the influence of extremely high soil P concentration on sugarcane sucrose concentration (KST, kg sucrose t^{-1} cane), since higher soil P concentration may be encountered in rotation with vegetables and has been shown to reduce KST (Andreis and McCray, 1998). Phosphorus fertilizer was banded for all treatments at all sites. Triple superphosphate (TSP) was used for all P applications except for ratoon crops 1 and 2 at Site 3 and ratoon crops 1 and 2 at Site 4, when monoammonium phosphate (MAP) was used as the P source. When MAP was used as the P source, all treatments were brought up to the N rate of 69 kg N ha^{-1} with ammonium sulfate. Except for the specific sites and years where MAP was used as the P source, no N was applied, since N is not recommended for sugarcane on organic soils in Florida (Rice et al., 2010). Monoammonium phosphate was used as the P source in the crop years specified to gain familiarity with the material because TSP has become less available to local growers since TSP is no longer produced in Florida. Potassium and micronutrients were applied to all plots at planting (K rates at planting ranged from 139 to 232 kg K ha^{-1}) based on University of Florida soil-test recommendations (Rice et al., 2010). Potassium was applied to all plots in ratoon crops (K rates for ratoon crops ranged from 139–167 kg K ha^{-1}) as per soil-test recommendations (Rice et al., 2010). The K source for all applications was muriate of potash. All fertilizer applications were banded in the furrow before planting or banded as sidedress applications on the soil surface along the side of each sugarcane row for ratoon crops. Sidedress applications to ratoon crops were made in March to early April each year.

Table 1. Characterization of test sites used for sugarcane P rate studies on Florida organic soils.

Site	Soil series	Soil pH†	Water-extractable P‡	Cultivar	Date established§
1	Terra Ceia	6.6	1.7	CL 77–797	Nov. 1995
2	Pahokee	4.8	9.0	CL 69–886	Dec. 1995
3	Dania	6.2	1.3	CP 80–1743	Nov. 2004
4	Pahokee	6.9	2.1	CP 89–2143	Mar. 2007

† Soil pH values were determined for 0- to 30-cm depth at Sites 1 and 2, and for 0- to 15-cm depth at Sites 3 and 4

‡ Water-extractable P values were determined for 0- to 30-cm depth for all sites. Reported values are means of 0- to 15- and 15- to 30-cm depths for Sites 3 and 4, respectively.

§ Tests at Sites 1 to 3 were established at planting. The test at Site 4 was established in the first ratoon crop.

Soil Sampling and Analyses

Soil samples were collected in the control (zero P) plots immediately after the first harvest of each test. Samples were collected in the row to a depth of 30 cm at Sites 1 and 2, and in the row at 0- to 15- and 15- to 30-cm depths at Sites 3 and 4. Soil samples were placed in aluminum drying pans, air-dried in a forced air drying room at 31°C and sieved through a 2-mm screen before analysis. Soil–water pH was determined for all soil samples using a 1:2 soil/water ratio. Values reported are for the 0- to 30-cm depth for Sites 1 and 2, and the 0- to 15-cm depth for Sites 3 and 4 (Table 1). Water-extractable P (Korndorfer et al., 1995) was reported for the 0- to 30-cm depth for all sites (Table 1). Water-extractable P values for the 0 to 15 cm and 15- to 30-cm depths were averaged for each plot to determine values for the 0- to 30-cm depth at Sites 3 and 4. Phosphorus concentrations were determined with a probe colorimeter using the phosphomolybdate blue method (Murphy and Riley, 1962).

Yield Measurements

For Sites 1 and 2, sugarcane harvest weights were taken by cutting and weighing the middle two rows of each plot with a commercial harvester and a harvest wagon equipped with a load cell. These weights were used to calculate TCH. Previous to collecting harvest biomass weights, 16-stalk samples were taken from the two middle rows of each plot for determination of KST. Stalk samples were milled and the crusher juice analyzed for Brix and pol. Brix, which is the percent soluble solids, was measured using a refractometer that automatically corrected for temperature. Pol, which is a unitless measure of the polarization of the sugar solution, was measured using a saccharimeter. The KST was determined according to the theoretical recoverable sugar method (Legendre, 1992). The TSH (t sucrose ha^{-1}) was calculated as the product of TCH

Table 2. For fixed effects in combined analysis of Sites 1, 2, and 3, $P > F$ for t cane ha^{-1} (TCH), sucrose concentration (KST), and t sucrose ha^{-1} (TSH).†

Source	TCH	KST	TSH
		$P > F$	
Site	<0.001	<0.001	<0.001
Crop	<0.265	0.032	0.600
P rate	0.003	0.084	0.002
Site × crop	<0.001	<0.001	<0.001
Site × P rate	<0.001	<0.001	0.009
Crop × P rate	0.014	0.665	0.005
Site × crop × P rate	0.141	0.006	0.394

† Test sites with results for all three of plant cane, first ratoon, and second ratoon crops were used for this analysis. Annual P rates were 0, 9, 18, 36, 72, and 144 kg P ha^{-1}.

and KST (divided by 1000 to convert kg sucrose to metric tons). Relative sucrose ha^{-1} was determined for each treatment for each crop year at each test site by dividing TSH for each treatment of each replication of each crop by the corresponding highest TSH value for that replication. Relative sucrose ha^{-1} is a relative yield term which allows for comparison of yield response across different years and locations (Evans, 1987).

Harvest dates for Site 1 were 25 to 26 Feb. 1997 (plant cane), 6 Mar. 1998 (first ratoon), 18 Feb. 1999 (second ratoon), and 25 Mar. 2000 (third ratoon). Harvest dates for Site 2 were 24 Jan. 1997 (plant cane), 6 Jan. 1998 (first ratoon), 27 Jan. 1999 (second ratoon), and 17 to 18 Feb. 2000 (third ratoon).

Stalk counts and stalk weights were used to calculate TCH at Sites 3 and 4. Millable stalks were counted in two of the middle four rows of each plot in August-September each crop year. Selection of the two rows for counting was based on representative stand uniformity. A 40-stalk random sample was used to determine fresh stalk weight, and TCH was calculated as the product of stalk number and stalk weight. To determine KST, a 10-stalk harvest random sample was milled and the crusher juice analyzed for Brix and pol using a NIR analyzer (Model 5000, Foss NIR Systems, Silver Spring, MD). The KST and TSH calculations were performed as described for Sites 1 and 2.

Stalk weight and KST measurements were performed for Site 3 on 19 to 20 Dec. 2005 (plant cane), 20 to 21 Nov. 2006 (first ratoon), and 17 to 18 Oct. 2007 (second ratoon). These measurements were performed for Site 4 on 4 Dec. 2007 (first ratoon) and 1 Dec. 2008 (second ratoon). After yield samples were taken, the remaining sugarcane was harvested commercially with machine harvesters. Site 3 plots were harvested on 22 Dec. 2005 (plant cane), 4 Dec. 2006 (first ratoon), and 19 Oct. 2007 (second ratoon). The plant cane crop at Site 4 was harvested on 1 Mar. 2007, just before establishment of the experiment. After yield samples were taken the following 2 yr, Site 4 plots were harvested on 17 Dec. 2007 (first ratoon) and 4 Feb. 2009 (second ratoon).

Statistical Analyses

All statistical analyses were performed using SAS version 9.2 (SAS Institute, 2008). Analysis of variance was performed for TCH, TSH, and KST for the plant, first ratoon, and second ratoon crops of Sites 1, 2, and 3 using the PROC MIXED procedure for a RCBD with site, crop year, and P rate treated as fixed effects and replication treated as a random effect to determine significant effects of site and interactions with site. Analysis of variance was also performed with the same dataset using the PROC MIXED procedure for a RCBD with site and replication treated as random effects and with crop year and P rate treated as fixed effects to determine significant effects of crop year and P rate and their interaction.

Analysis of variance was performed individually for TCH, TSH, KST, fresh stalk weight, and stalk population (stalks m^{-1} row) for Sites 1, 2, 3, and 4 across crop years using the PROC GLM procedure for a RCBD with replication, crop year, and P rate treated as fixed effects. Linear and quadratic regressions were performed using values for individual plots as appropriate for means across crop years or for individual crop years depending on significance ($P < 0.05$) of F tests for P rate and the interaction of crop year and P rate. Regressions were performed as appropriate for TCH, TSH, and KST for all sites, and for stalk weight and stalk population for Sites 3 and 4. These regressions were performed for TCH, TSH, stalk weight, and stalk population using only P rates 0 to 72 kg P ha^{-1}, because the 144 kg P ha^{-1} rate was included specifically to examine the influence of high soil P on KST. Phosphorus rates required to reach the predicted maximum TCH and TSH, and 95% of these predicted maximums, were estimated using the quadratic model if the quadratic term was significant ($P < 0.05$). The linear regression was used for these estimates if the linear regression was significant and the quadratic term was not significant. In situations when there was a significant effect of P rate for a given parameter, and linear and quadratic regressions were nonsignificant, preplanned single degree of freedom contrasts were used to determine significance between treatments. Selected contrasts included a comparison between the zero P rate and the mean of rates 9 to 144 kg P ha^{-1} to determine if there was a significant response to P fertilizer overall. In addition, each P rate greater than zero was contrasted with the next highest P rate to determine if doubling the P rate resulted in a significant difference in measured response. Least significant difference ($P < 0.05$) was also determined for each analysis of variance procedure as appropriate for each site for TCH, TSH, KST, stalk weight, and stalk population.

Analysis of variance was also performed for relative sucrose ha^{-1} for the zero P treatment to determine the effect of crop year on this parameter at each site. The PROC GLM procedure for a RCBD was used with replication, crop year, and P rate treated as fixed effects. Comparison of treatment means was done using least significant difference at $P = 0.05$.

RESULTS

When Sites 1, 2, and 3 were analyzed together across the plant cane, first ratoon, and second ratoon crops, TCH, KST, and TSH were significantly influenced by site and by the interactions of site with crop year and site with P rate (Table 2). The three-way interaction of site, crop year, and P rate also significantly influenced KST. Phosphorus rate and the interaction of crop year and P rate significantly affected TCH and TSH.

At Site 1, crop year and P rate each significantly influenced TCH, TSH, and KST (Table 3). There was not a significant interaction between crop year and P rate for TCH, TSH, or KST so P responses were compared by combining means of all crop years for these parameters (Fig. 1). Only P rates from 0 to 72 kg P ha^{-1} were considered in the regression models for TCH and TSH. Linear

Table 3. For fixed effects in analyses of each site, *P* > *F* for t cane ha^{-1} (TCH), sucrose concentration (KST), and t sucrose ha^{-1} (TSH).†

Source	Site 1			Site 2			Site 3			Site 4		
	TCH	KST	TSH	TCH	KST	TSH	TCH	KST	TSH	TCH	KST	TSH
	P > F											
Crop	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
P rate	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.022	0.962	0.079	<0.001	<0.001	<0.001
Crop × P rate	0.292	0.165	0.255	<0.001	0.626	<0.001	0.734	0.585	0.761	0.441	0.007	0.517

† There were four crop years at Sites 1 and 2 (plant cane through third ratoon), three crop years at Site 3 (plant cane through second ratoon), and two crop years at Site 4 (first and second ratoon). Annual P rates were banded at 0, 9, 18, 36, 72, and 144 kg P ha^{-1}.

and quadratic models were significant for 4-yr TCH and TSH means (Fig. 1a, b). Since the quadratic models for both parameters significantly improved the regressions, the quadratic models were used to estimate the P rate required to reach maximum TCH and TSH. The maximum TCH and TSH were predicted at 49 and 46 kg P ha^{-1}, with 95% of maximum TCH and TSH predicted at 27 and 25 kg P ha^{-1}, respectively. Sucrose concentration (KST) decreased linearly at the rate of 0.037 kg t^{-1} with each unit increase in P fertilizer (Fig. 1c). The decrease in KST between 0 and 72 kg P ha^{-1} did not change predicted P rate requirements substantially for TSH compared with TCH at Site 1.

Crop year and P rate each significantly influenced TCH, KST, and TSH at Site 2 (Table 3). Also, there was a significant interaction between crop year and P rate for TCH and TSH. Linear and quadratic regressions of P rate with TCH were significant for each crop year (Fig. 2). As at Site 1, the quadratic regressions significantly improved the relationship between P rate and TCH, as compared with the linear regressions. There were steeper increases in TCH with increasing P rate up to maximum predicted TCH in the second and third ratoon crops as compared with plant cane and first ratoon (Fig. 2b), which explains the interaction between crop year and P rate (Table 3). Phosphorus rate required to reach maximum TCH as predicted by the quadratic models ranged from 45 to 56 kg P ha^{-1} for the four crop years with slightly reduced P rates required in later crops. The P fertilizer rate required to reach 95% of maximum predicted TCH ranged from 25 to 33 kg P ha^{-1} with no clear trend with crop year. Tonnes cane ha^{-1} was higher for some P rates for the second ratoon crop than the two previous crops which is unusual, but P fertilizer requirement in the second ratoon crop (33 kg P ha^{-1} at 95% of maximum predicted TCH) was similar to other crop years.

Only the linear regression model was significant relating P rate to TSH for the plant cane crop at Site 2 (Fig. 3). Only the quadratic model was significant for the first ratoon crop, and quadratic models were also significant for the second and third ratoon crops. Similar to responses in TCH, increases in TSH with increasing P rate were steeper up to maximum predicted TSH in the second and third ratoon crops as compared with plant cane and first ratoon (Fig. 3b). These stronger responses to P fertilizer in the later crop years were also indicated by the lower relative sucrose ha^{-1} with no P fertilizer in these years at Site 2 (Table 4). The interaction between P rate and crop year is explained by the differences in linear and quadratic responses for different years and also by the stronger TSH response in the second and third ratoon crops compared with the previous 2 yr. Using the linear model for plant cane predicted a maximum TSH with a P rate of 72 kg P ha^{-1}. However, the TSH actually measured at the 36 kg P ha^{-1} rate was within 1% of that measured at 72 kg P ha^{-1}. Measured TSH means at 36 kg P ha^{-1} were slightly

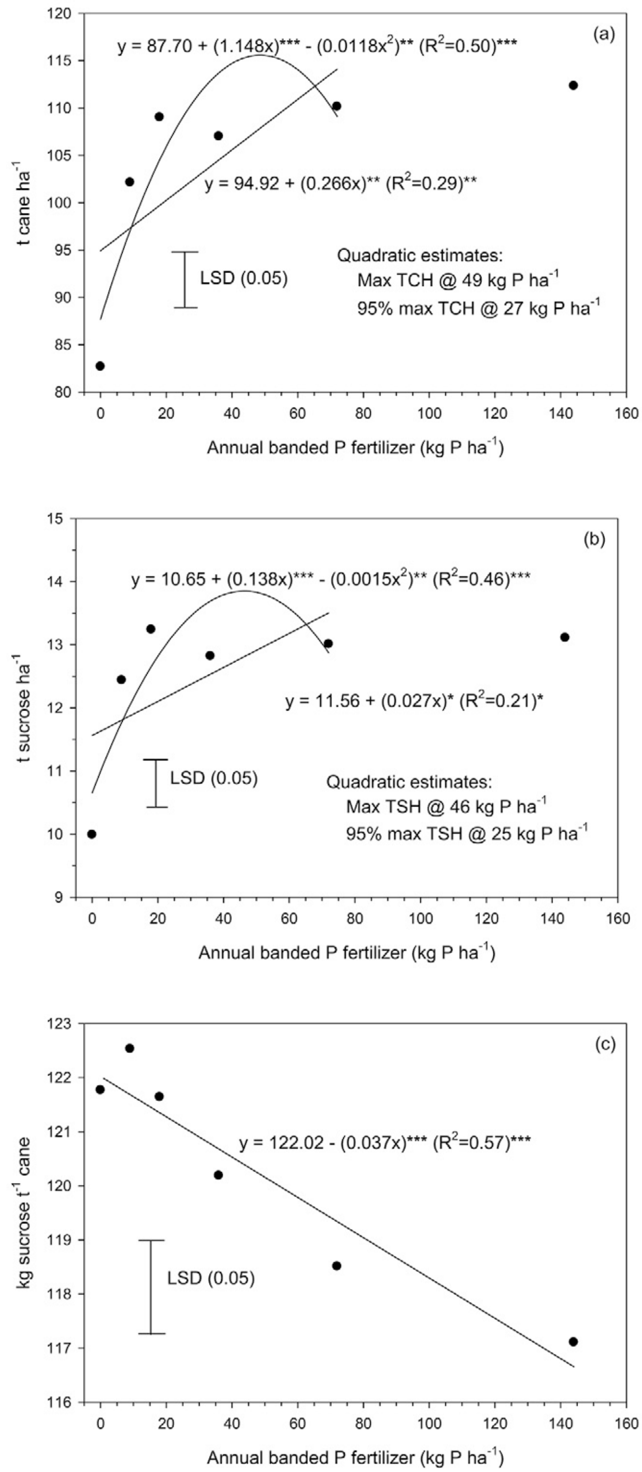
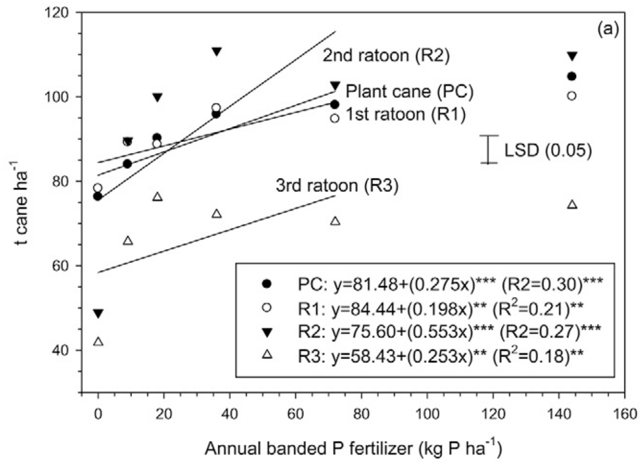


Fig. 1. Relationships between annual banded P fertilizer rate and (a) t cane ha^{-1} (TCH), (b) t sucrose ha^{-1} (TSH), and (c) kg sucrose t^{-1} cane (KST) for 4-yr means at Site 1.



Estimates of required kg P ha^{-1}			
Crop	Model	Max TCH	95% max TCH
PC	Quad	56	30
R1	Quad	50	25
R2	Quad	46	33
R3	Quad	45	30

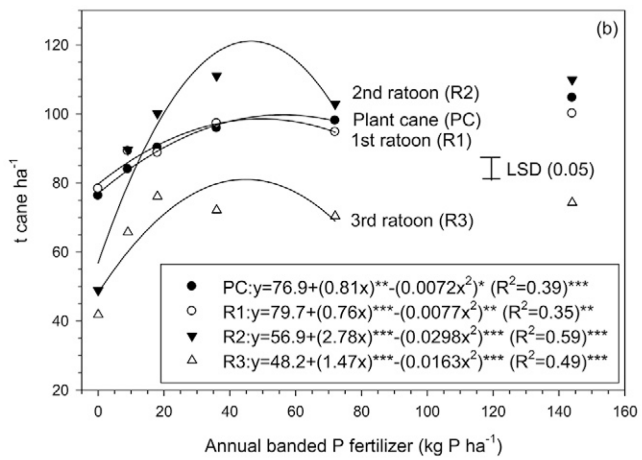
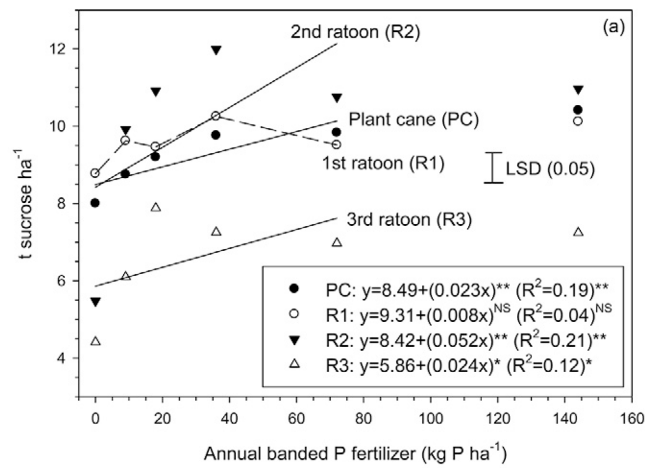


Fig. 2. Relationships between annual banded P fertilizer rate and t cane ha^{-1} (TCH) for each crop year at Site 2 using (a) linear and (b) quadratic regression.



Estimates of required kg P ha^{-1}			
Crop	Model	Max TSH	95% max TSH
PC	Linear	72	50
R1	Quad	42	17
R2	Quad	45	31
R3	Quad	44	29

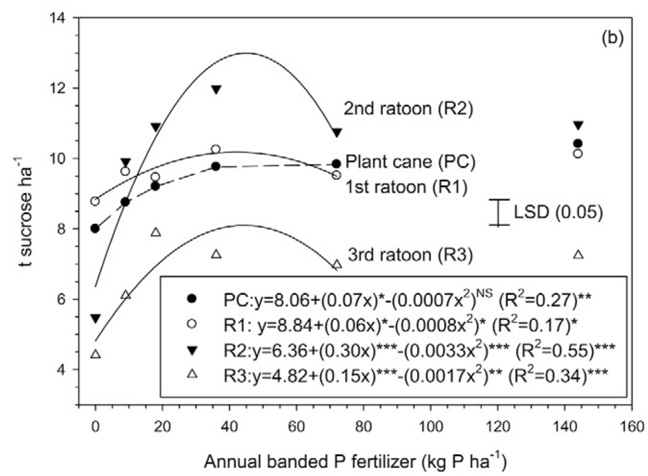


Fig. 3. Relationships between annual banded P fertilizer rate and t sucrose ha^{-1} (TSH) for each crop year at Site 2 using (a) linear and (b) quadratic regression.

higher numerically as compared with means at the 72 kg P ha^{-1} rate for the first through third ratoon crops. The quadratic models for first through third ratoon predicted maximum TSH at 42 to 45 kg P ha^{-1}, with 95% of maximum TSH predicted at 17 to 31 kg P ha^{-1}. There was a significant linear decrease in KST at the rate of 0.053 kg t^{-1} with each unit increase in P fertilizer (Fig. 4).

At Site 3, crop year significantly influenced TCH, KST, and TSH (Table 3). Phosphorus fertilizer rate significantly influenced TCH, but not KST or TSH. The interaction between crop year and P rate was not significant for TCH, KST, or TSH. Neither the linear or quadratic regression models relating P rate with TCH 3-yr means were significant (Fig. 5a). Because linear and quadratic regressions were not useful for determining an optimum P rate for Site 3, contrasts were used to determine differences in TCH means between P rates. There were no contrasts that were significant at $P = 0.05$, but the contrast comparing zero P with the mean of rates 9 to 144 kg P ha^{-1} ($P = 0.059$), and the contrast comparing 9 and 18 kg P ha^{-1} ($P = 0.083$) were significant at $P < 0.10$. Also, because there were no significant differences in KST between P rates (Table 3), the relationships of P rate with TCH and TSH (Fig. 5b) were similar. Although the response to P fertilizer was less at Site 3 compared with the other sites, contrasts suggested some response in TCH to the 18 kg P ha^{-1} rate applied each crop year (Fig. 5a).

Crop year and P fertilizer rate significantly influenced TCH, KST, and TSH at Site 4 (Table 3). Interaction between crop year and P rate significantly influenced KST but not TCH or TSH. Linear and quadratic regression models relating P rate to 2-yr TCH and TSH means were significant (Fig. 6a, b). Quadratic models predicted that P rate requirement to achieve maximum TCH and TSH were 51 and 49 kg P ha^{-1}, with 95% of maximum TCH and TSH requiring 33 and 32 kg P ha^{-1}, respectively. Even though relative sucrose ha^{-1} without P fertilizer at Site 4 was 0.66 in the first ratoon crop and 0.38 in the second ratoon crop (Table 4), the P fertilizer requirement was similar each year. There was a linear decrease in KST with increasing P rate in the first ratoon crop (Fig. 6c). A quadratic response in the second ratoon crop indicated that

KST declined up to a P fertilizer rate of about 80 kg ha^{-1}, and then higher P rates resulted in moderate increases in KST. However, we do not consider this increase in KST at Site 4 as indicative of KST response to P fertilizer based on responses at Sites 1 to 3 as well as our previous research and that of others.

Evaluations of the effects of P fertilizer rate on stalk weight and stalk population were only available for Sites 3 and 4. At Site 3, crop year significantly influenced stalk weight, but P rate was not significant across years (Table 5). Although the interaction between crop year and P rate was not significant (Table 5), stalk weight increased quadratically with P rate (0–72 kg P ha^{-1}) in the second ratoon crop (Fig. 7a). There was a significant influence of P rate on stalk population across crop years at Site 3 (Table 5). There was a significant linear increase in stalk population (3-yr mean) with P rate up to 72 kg P ha^{-1} (Fig. 7b). At Site 4, stalk weight and stalk population were significantly influenced by crop year and P rate (Table 5). Mean stalk weight of first and second ratoon crops were 1.27 and 1.03 kg, respectively, and mean stalk population of first and second ratoon crops were 14.1 and 13.2 stalks m^{-1}, respectively (data not shown). The interaction of crop year and P rate did not significantly affect either parameter. Linear and quadratic regression models were each significant for 2-yr means of stalk weight and stalk population as related to P rate up to 72 kg P ha^{-1} (Fig. 8). The largest increase in stalk weight and stalk population with P fertilizer was between the 0 and 9 kg P ha^{-1} rates.

DISCUSSION

Maximum Phosphorus Fertilizer Recommendation

These sugarcane trials document significant responses in TCH and TSH to P fertilizer on organic soils. With the exception of one crop year at Site 2 (Fig. 3), quadratic regression models resulted in improved relationships of TCH and TSH with P rate compared with linear models for Sites 1, 2, and 4. There was a significant response in TCH to P fertilizer at Site 3, but linear and quadratic regression models were not significant in relating TCH with P rate. Quadratic regressions at Sites 1, 2, and 4 predicted maximum TCH and TSH at P rates between 36 and 72 kg P ha^{-1} (Fig. 1, 2, 3, and 6). The quadratic regression models were developed using P rates 0 to 72 kg ha^{-1} and generally suggest that at rates approaching 72 kg P ha^{-1}, TCH and TSH were decreasing faster than actually observed, as determined by measured values at the higher 144 kg P ha^{-1} rate. While TSH could be decreasing approaching 72 kg P ha^{-1} because of decreasing KST with increasing P rate (Fig. 1c, 4, and 6c), TCH (a measure of biomass) would not be expected to decrease as P fertilizer approaches 72 kg P ha^{-1}. In some cases predicted maximum TCH or TSH values were higher than actually measured at any rate. Also, predicted P rate increases of 39 to 147% were predicted as required to increase TCH or TSH from 95 to 100% of maximum (Fig. 1, 2, 3, and 6). To avoid overestimation of P requirement, we used the P fertilizer rate required to achieve 95% of maximum, rather than the absolute maximum TCH or TSH.

The highest P fertilizer rate predicted to achieve 95% of maximum TCH or TSH at Sites 1, 2, and 4 was 33 kg P ha^{-1} (Fig. 1, 2, 3, and 6). Linear regression for the plant cane crop at Site 2 ($R^2 = 0.19$) predicted 50 kg P ha^{-1} to achieve 95% of maximum TSH (Fig. 3), but measured TSH means at 36 and 72 kg P ha^{-1} differed by <1%. At Site 3, linear and quadratic regressions relating P rate and TCH were not significant, but 18 kg P ha^{-1} was indicated by contrasts ($P < 0.10$) as an appropriate rate (Fig. 5a).

Table 4. Relative sucrose ha^{-1} with no P fertilizer for each crop at each P rate test site. †

Crop year	Site 1	Site 2	Site 3	Site 4
	Relative sucrose ha^{-1} with no P fertilizer			
Plant cane	0.74	0.75	0.85	—
first ratoon	0.75	0.83	0.85	0.66
second ratoon	0.66	0.42	0.80	0.38
third ratoon	0.62	0.52	—	—
Crop year ($P < F$)	<0.001	<0.001	0.819	0.023
LSD (0.05)	0.06	0.13	0.18	0.22

† Relative sucrose ha^{-1} for each 0 P treatment for each crop year at each test site was determined by dividing TSH for the 0 P treatment of each replication of each crop by the highest TSH value for that replication. Phosphorus fertilizer rates were 0, 9, 18, 36, 72, and 144 kg P ha^{-1}. Crop years with missing values were not included in the study.

Andreis and McCray (1998) reported that a P fertilizer rate of 36 kg ha^{-1} was sufficient for organic soils testing low in Bray 2-extractable P. Glaz et al. (2000a) measured yield responses at 48 kg P ha^{-1} compared with 24 kg P ha^{-1} for some crop year and location combinations, but did not have a 36 kg P ha^{-1} rate to determine if there were responses between 36 and 48 kg P ha^{-1}. Coale et al. (1993) reported that a ratoon crop with a mean harvest TCH of 103 Mg ha^{-1} had a total accumulation of 38 kg P ha^{-1} of which 23 kg P ha^{-1} was removed from the field as crop harvest. Supplying a maximum of 36 kg P ha^{-1} would supply almost as much P as is taken up by the crop and approximately 1.5 times the amount of P removed by a typical harvest. Diaz et al. (1993) found P mineralization rates for drained Florida organic soils to range from 5.6 to 72 kg P ha^{-1} yr^{-1}, indicating that plant-available P is provided by mineralization each year, but that the amount is highly variable. Coale et al. (1993) determined that crop harvest removed 179% of P fertilizer applied, indicating that the crop was using P from other sources in addition to fertilizer P, including P mineralization and other soil P reserves. Our study included soils with very low P availability as indicated by relative sucrose ha^{-1} without P fertilizer as low as 0.38 (Table 4). Based on estimated crop

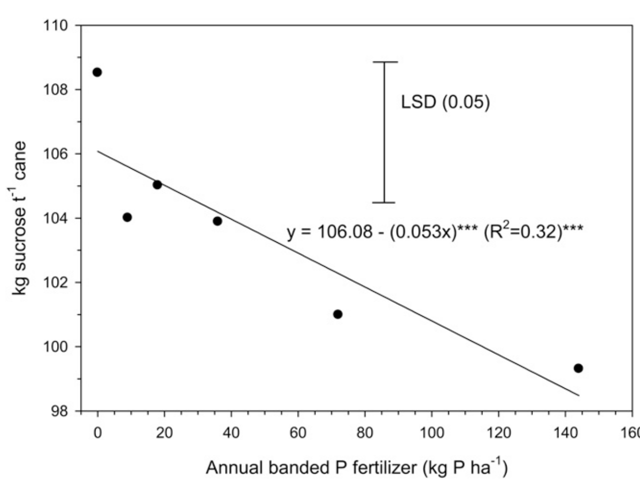


Fig. 4. Relationship between annual banded P fertilizer rate and 4-yr means of kg sucrose t^{-1} cane (KST) at Site 2.

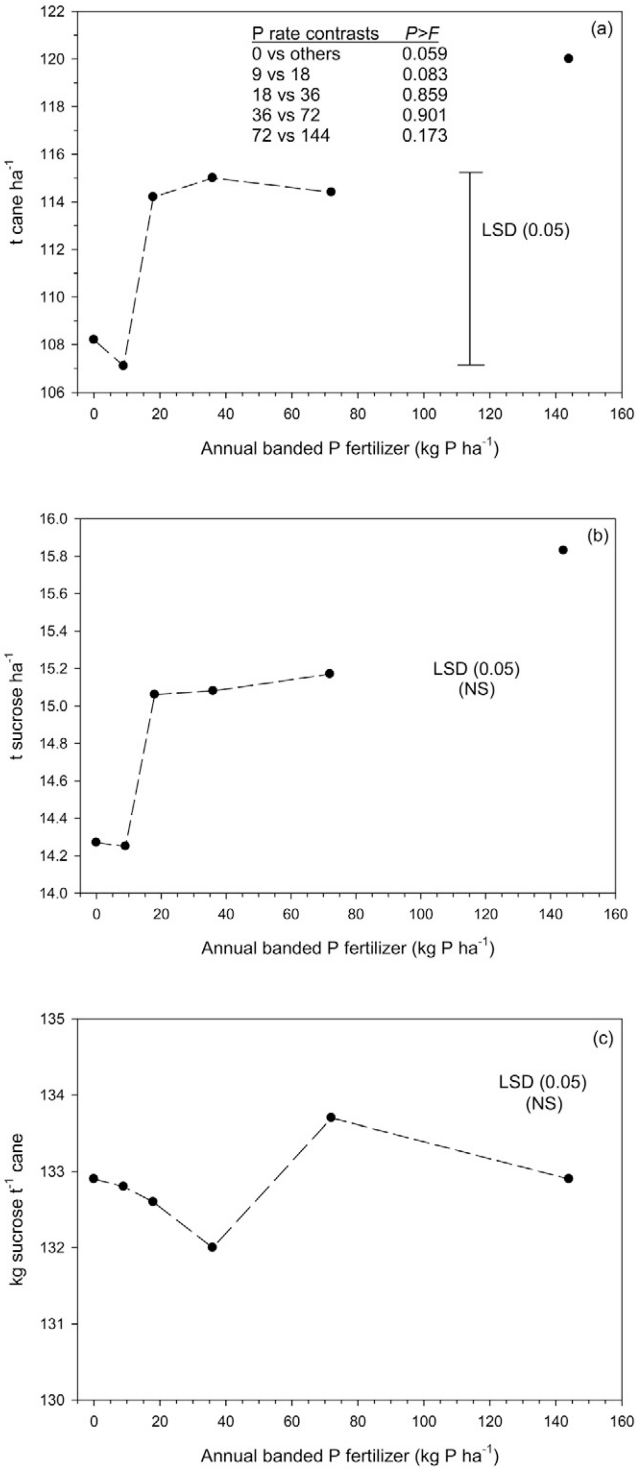


Fig. 5. Relationships between annual banded P fertilizer rate and (a) t cane ha^{-1} (TCH), (b) t sucrose ha^{-1} (TSH), and (c) kg sucrose t^{-1} cane (KST) for 3-yr means at Site 3. Linear and quadratic regression models were not significant for TCH, so contrasts between P rates are included.

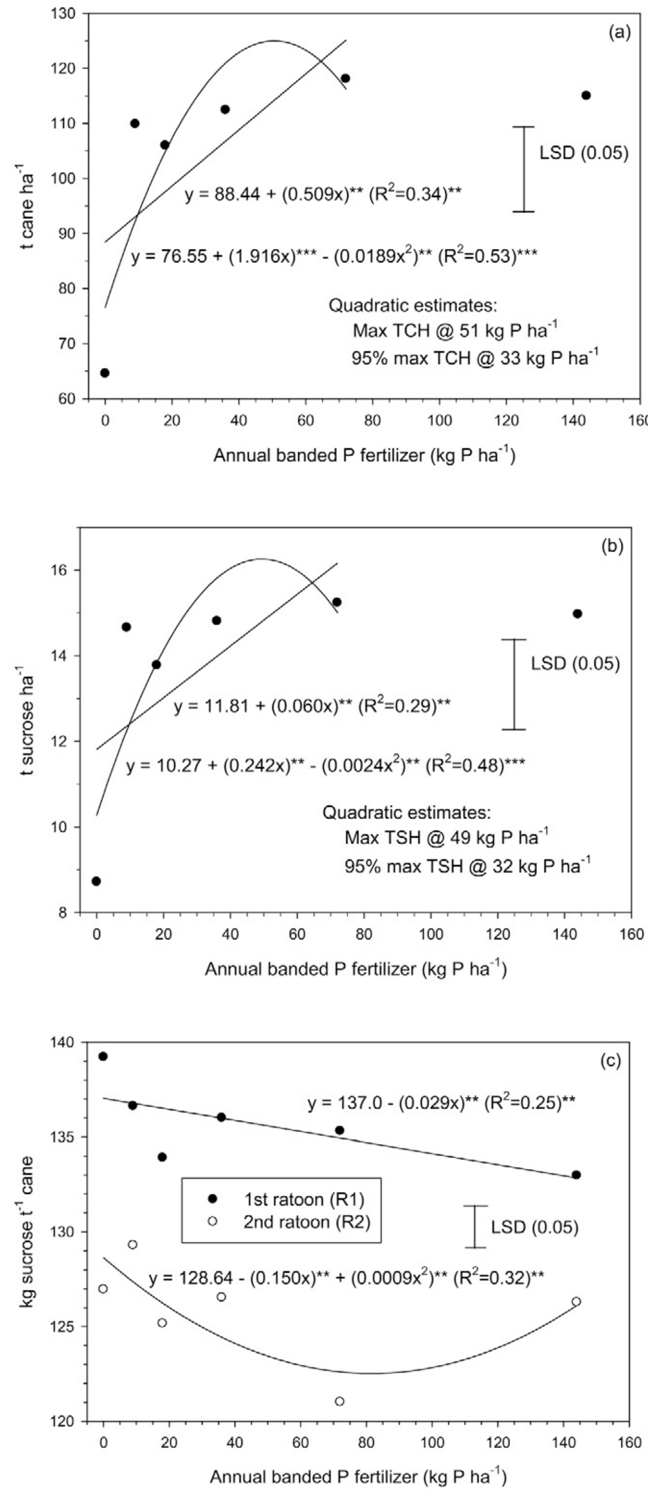


Fig. 6. Relationships between annual banded P fertilizer rate and (a) t cane ha^{-1} (TCH), (b) t sucrose ha^{-1} (TSH), and (c) kg sucrose t^{-1} cane (KST) for 2-yr means at Site 4.

requirement being ≤33 kg P ha^{-1}, our results support maintaining the maximum P fertilizer rate at 36 kg P ha^{-1} for soils with extremely low P availability, as is currently recommended (Gascho and Kidder, 1979; Gilbert and Rice, 2009). The recommendations of Gascho and Kidder (1979) were based on studies using broadcast application and this study used banded application. The maximum recommended P rate remains unchanged although banded application at a given P rate was more effective with other crops on organic soils (Sanchez et al., 1990). Because of soil subsidence, soils have continued to become shallower in the last three decades (Wright and Snyder, 2009), which has resulted in increased pH and decreased P and micronutrient availability as Ca carbonate from the underlying limestone is mixed into the root zone (Wright et al., 2009). Shallower soils can mean increased difficulty with drainage and irrigation as well as shallower water tables. Growers may also be maintaining shallower water tables during the rainy season of June-October as part of BMP requirements as compared with 30 yr ago (Glaz and Gilbert, 2006). Higher water tables may result in more frequent flooding and draining which increases P mineralization in the root zone (Diaz et al., 1993). Also, while there have been gains in TSH in sugarcane cultivars over the last three decades, these gains have been more associated with a greater allocation of assimilates toward sucrose accumulation, with smaller increases in TCH (Edme et al., 2005), so that P requirement of current cultivars may not have changed to a large degree. Overall, factors related to water management, including crop water availability and drainage, have probably been impacted by changes in the last 30 yr more than sugarcane P fertilizer requirement. The increased efficiency of banding P fertilizer compared to broadcast application should be adequate to meet the small increase in P fertilizer requirement that may have developed over the last three decades as a result of shallower soils and a small increase in TCH.

Determination of Specific Phosphorus Requirement

Because site and cultivar were confounded in this study, it was not possible to examine the effect of cultivar on yield response to P fertilizer. While there can be minor differences between genotypes in terms of P uptake and yield response, interactions between genotype and P fertilizer rate have been found generally not significant (Glaz et al., 2000b). Also, our study was conducted over a period of approximately 13 calendar years from the beginning of the test at Site 1 until the conclusion of the test at Site 4 so test site and calendar year were confounded. The unexpected increase in TCH and TSH for some P rates in the second ratoon crop at Site 2 as compared with plant cane and first ratoon crops (Fig. 2) suggests that calendar year affected yields. Because of the influence of rainfall and other weather-related factors, calendar year can be expected to be important in yield determination along with the factors of site, crop year, and P rate. There were indications that P deficiency became more acute in later crop years. Evidence of this was determined with relative sucrose ha^{-1} without P fertilizer in successive crops, particularly with second and third ratoon crops compared with plant cane and first ratoon at Sites 1 and 2, and second ratoon compared with first ratoon at Site 4 (Table 4). Gascho and Kidder (1979) noted that sugar yield responses to P fertilization were more apparent in ratoon crops than in plant cane. Andreis and McCray (1998) only observed positive TSH responses in ratoon crops in some experiments. In our current study, there were significant interactions between crop year and P rate for TCH and TSH at Site 2 (Table 3), which were explained by stronger yield responses to P fertilizer in the second and third ratoon crops compared with plant cane and first ratoon (Fig. 2 and 3). At other sites the interactions of crop year and P rate for TCH and TSH were not significant (Table 3). Even though P deficiency may become more acute with successive crops when no P fertilizer is applied and the response to P fertilizer may be stronger in later ratoon crops, this study did not indicate a consistently higher P fertilizer requirement in later years of a crop cycle. A uniform P rate across crop years for a given location should adequately meet the crop P requirement of sugarcane.

Table 5. For fixed effects in analyses of Sites 3 and 4, *P > F* for stalk weight and stalk population.†

Source	Site 3 Stalk wt.	Site 3 Stalk no.	Site 4 Stalk wt.	Site 4 Stalk no.
		P > F		
Crop	<0.001	0.155	<0.001	0.033
P rate	0.227	0.040	<0.001	<0.001
Crop × P rate	0.650	0.077	0.428	0.077

† There were three crop years at Site 3 (plant cane through second ratoon) and two crop years at Site 4 (first and second ratoon). Annual P rates were banded at 0, 9, 18, 36, 72, and 144 kg P ha^{-1}.

Responses were generally similar in TSH and TCH, although there were some differences such as the slight difference in significance of the effect of P rate on TCH and TSH at Site 3 (Table 3). There was a significant linear reduction of KST with increasing P through the 144 kg P ha^{-1} rate at Sites 1 and 2 (Fig. 1c and 4), and for the first ratoon crop at Site 4 (Fig. 6c). Reduced KST with increased P fertilization has been observed in other studies (Andreis and McCray, 1998; Gascho and Kidder, 1979) and is more pronounced at elevated soil test P levels. Meyer and Wood (1989) reported that application of P fertilizer did not affect sugarcane sucrose levels significantly. In our study there was <5% reduction in KST for rates ≤36 kg P ha^{-1} compared with zero P. We found that the negative influence of P on KST was less than the positive effects of increased P on TCH.

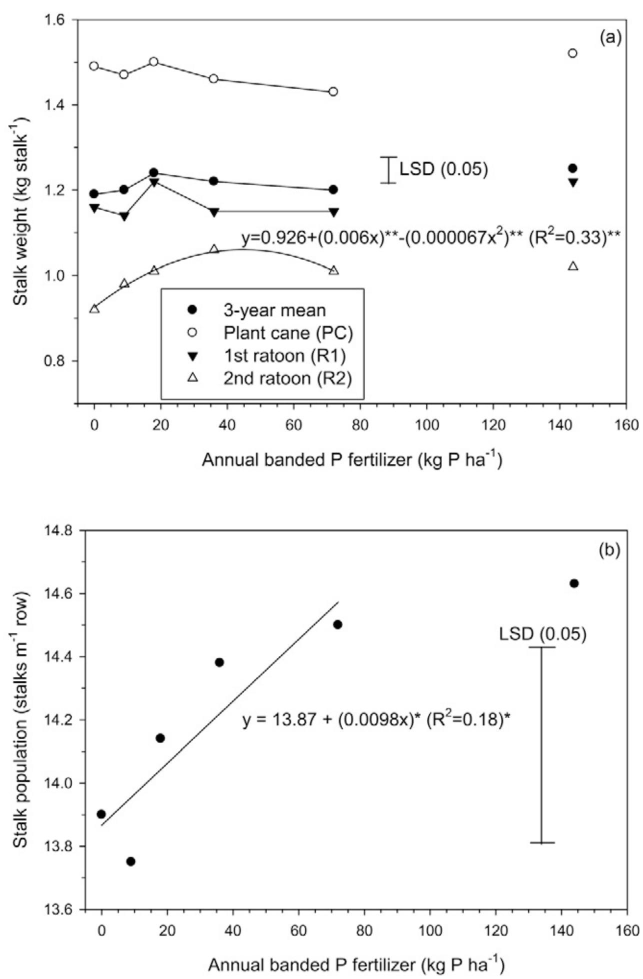


Fig. 7. Relationships between annual banded P fertilizer rate and (a) stalk weight (3-yr means and individual crop years) and (b) stalk population (3-yr means) at Site 3.

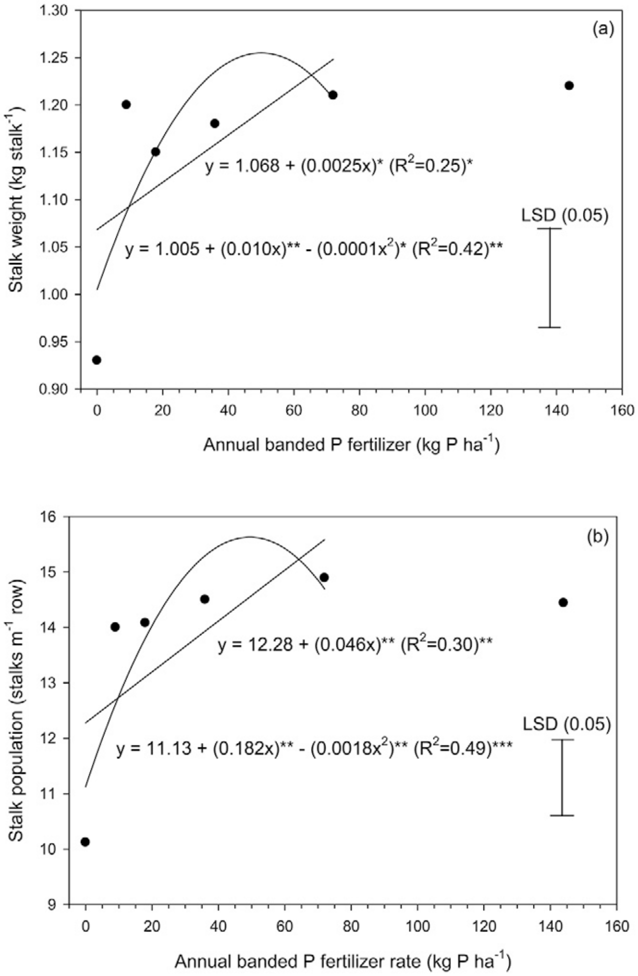


Fig. 8. Relationships between annual banded P fertilizer rate and 2-yr means of (a) stalk weight and (b) stalk population at Site 4.

Gascho and Kidder (1979) reported that sugarcane stalk weight and stalk population were each affected by P fertilization, but that while stalk population increased linearly with P rate, TSH increased quadratically. Both stalk weight and stalk population were also increased by P fertilization in our study, with each increasing quadratically at Site 4 where there was severe P deficiency (Fig. 8). Stalk population was more influenced than stalk weight at Site 3 where there was a smaller TCH response to fertilizer (Fig. 7).

As discussed, responses in TCH and TSH were similar within sites, and P requirements were similar across crop years within sites. Using quadratic regression for Sites 1, 2, and 4 (Fig. 1, 2, 3, and 6), the highest rate required to achieve 95% TCH or TSH overall or for individual crop years was chosen as the appropriate P fertilizer rate for each crop year at each site. For Site 3, the 18 kg P ha^{-1} rate was chosen based on contrasts for TCH response (Fig. 5a). Phosphorus fertilizer requirement was inversely related to relative sucrose ha^{-1} without P fertilizer (Fig. 9).

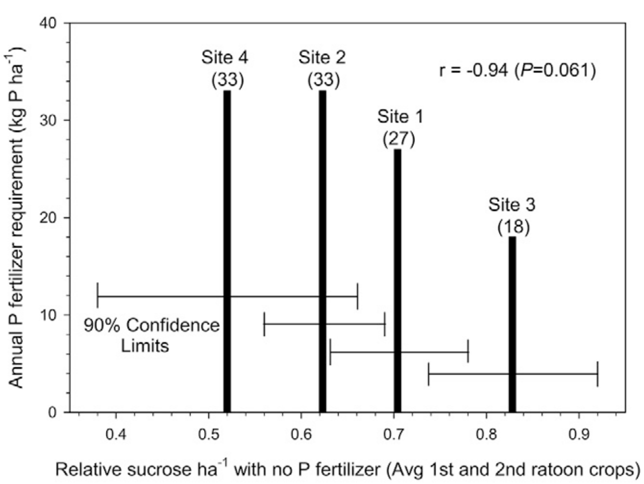


Fig. 9. Relationship between relative sucrose ha^{-1} with no P fertilizer and annual P fertilizer requirement for the average of first and second ratoon crops of all four sites. Relative sucrose ha^{-1} was determined by dividing TSH for the zero P treatment of each replication of each crop by the highest TSH value for that replication.

Determination of P fertilizer recommendations for sugarcane in Florida requires an improved calibrated soil test. The strong response in TCH and TSH to P fertilizer at Site 2 (Table 3) demonstrates that there is a need to improve the current soil test calibration, which is based on water-extractable P. Phosphorus fertilizer inputs are currently recommended for plant cane, first ratoon, and second ratoon crops on soils with water-extractable P ≤ 4.4, 5.1, and 6.6 g P m^{-3}, respectively (Gascho and Kidder, 1979), yet water-extractable P at Site 2 was 9.0 g P m^{-3} (Table 1). Water-extractable P at the other three sites ranged from 1.3 to 2.1 g P m^{-3}, and there were TCH responses to P fertilizer at all these sites. The water extractant is highly pH dependent, with increased P extracted at lower pH, as with the pH of 4.8 at Site 2. Also, the water-extractable P test was originally developed for short-term crops such as vegetables (Forsee, 1950) because it measures quickly available P. An improved soil test P calibration for organic soils in Florida will require an extractant that works well through a wide range of soil pH (typically <5 to near 8) and includes a measurement of reserve P as well as quickly available P.

CONCLUSIONS

The need for an updated soil test P calibration was demonstrated. Annual P fertilizer requirement at the four test sites ranged from 18 to 33 kg P ha^{-1}, with no consistent change in P requirement in different crop years. Phosphorus requirement was inversely related to relative sucrose ha^{-1} without P fertilizer. Based on measured responses to 33 kg P ha^{-1}, the maximum P fertilizer recommendation for Florida Histosols should be maintained at 36 kg P ha^{-1}. This maximum P rate was determined based on experiments with banded P fertilizer comparisons, since banding P fertilizer on sugarcane in the EAA is a BMP intended to reduce P application rates and subsequent P discharge. However, our recommended P rates were not reduced compared with previously recommended rates that were based on broadcast P applications. Linear reductions in KST should be expected at the recommended P fertilization rates ≤36 kg P ha^{-1}, but due to expected increases in TCH, the combined effects on TSH are expected to be positive.

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