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Phosphorus Fertilizer Calibration for Sugarcane on Everglades Histosols

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*A calibrated soil test for phosphorus (P) fertilizer application to sugarcane (*Saccharum *spp.) grown on organic soils in southern Florida is an important best-management practice for minimizing P loads in water draining to the Everglades. The current calibration uses water as the soil extractant, which has the limitations of being very sensitive to pH and being most applicable to short-season crops. Phosphorus fertilizer rate studies at six locations (20 total crop years) were analyzed to develop an updated soil-test P calibration for sugarcane on organic soils. Phosphorus extracted with water, acetic acid, and Bray 2 did not consistently relate well to crop response. A new P soil-test calibration for sugarcane is proposed based on Mehlich 3 soil extraction, with a maximum rate of 36 kg P ha^{-1} with $\leq$ 10 g P m^{-3} in preplant soil samples and no P recommended with $>$30 g P m^{-3}.*

Keywords Fertilizer calibration, Histosol, phosphorus, soil testing, sugarcane

Introduction

The Everglades Agricultural Area (EAA) is an area of 280,000 ha located south and east of Lake Okeechobee in southern Florida. The EAA is comprised predominately of Histosols having high organic-matter contents (30–90%) and shallow water tables. Sugarcane (*Saccharum* spp.) is grown on 157,000 ha in southern Florida, with approximately 80% of this hectarage on organic soils (Rice, Baucum, and Glaz 2009). Because the Everglades is a historically phosphorus-limited system, phosphorus (P) loads carried in EAA drainage water are a major environmental concern. Increased P concentrations have been found to accelerate eutrophication of natural Everglades wetlands (Bottcher, Tremwel, and Campbell 1995) and result in changes in vegetation communities (Gaiser et al. 2005; Noe et al. 2002; Reddy et al. 1998). The Everglades Forever Act (Florida State Statutes 1994) requires annual P loads in EAA basin drainage be reduced by at least 25% relative to historic baseline trends documented in 1978–1988 basin drainage data (Whalen and Whalen 1996). To achieve these basin-level P-load reduction targets, Florida sugarcane growers are required to use best-management practices

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(BMPs) designed to reduce P loads in farm drainage water (Rice, Izuno, and Garcia 2002). Soil testing for determination of appropriate P fertilizer rates 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). Water-extractable P is a soil test developed primarily for vegetable fertilizer recommendations in Florida (Forsee 1950). Compared to sugarcane, most vegetable crops require greater levels of available soil P (Hochmuth et al. 2009) during a crop growing season that is significantly shorter than sugarcane. Because sugarcane has a growing season of 8–16 months in Florida (typically more than 12 months for plant cane), various researchers have suggested that a soil test that includes some measure of reserve P would be an improvement over the water extractant (Glaz et al. 2000; Korndorfer et al. 1995). Soluble P is released in organic soils as organic matter is decomposed, with typical soil P-mineralization rates in the EAA ranging from 16 to 23 kg P ha^{-1} yr^{-1} (Reddy 1983). Mineralization rates vary with soil wetness, with greater P release occurring under periodic flooding and draining (Diaz, Anderson, and Hanlon 1993). A substantial portion of total P in EAA organic soils is composed of inorganic P fractions (Reddy et al. 1998). Castillo and Wright (2008) determined that a high proportion (41%) of total P in an EAA soil cropped to sugarcane (pH 6.8) was in the calcium-bound fraction. An improved soil-test P calibration for sugarcane will likely require an extractant chemistry that allows for a measure of slowly available P from the organic and inorganic soil-P fractions.

There has been a substantial amount of work in recent years comparing water to other extractant chemistries in an effort to update the soil-test P calibration for sugarcane. Korndorfer et al. (1995) compared water, Mehlich 1, and 0.5 M acetic acid (CH_3COOH) as P extractants and determined that acetic acid–extractable soil P related best to sugarcane crop response. Andreis and McCray (1998) developed a soil-test calibration for sugarcane using the Bray 2 extractant. One limitation of the water extractant is that it is very sensitive to pH, with more P extracted at lower pH. Research with vegetables on organic soils in Florida has suggested that the Mehlich 3 extractant performs satisfactorily over a wider pH range than water (Hochmuth et al. 2009). Mehlich 3 has been determined to be useful as an P extractant on a wide range of soil types (Hanlon and Johnson 1984; Tran et al. 1990) and has the advantage of potentially being used for extraction of macro- and micronutrients (Mehlich 1984).

Currently, fertilizer P is recommended for plant cane, first ratoon, and second ratoon crops on soils with water-extractable P $\leq$ 4.4, 5.1, and 6.6 g m^{-3} (Gascho and Kidder 1979; Rice, Gilbert, and McCray 2010). Banding P fertilizer is recommended as a BMP to maximize fertilizer-use efficiency (Lang et al. 2006). A maximum rate of 36 kg P ha^{-1} is recommended (Gascho and Kidder 1979) for plant and first ratoon crops with water-extractable P $\leq$ 0.75 g m^{-3}. From agronomic and environmental perspectives it is vital to have an effective soil-test P calibration for sugarcane on organic soils in south Florida. Given the limitations of the current water-extractable P soil test, there is a need for an updated soil-test calibration that incorporates more sophisticated extraction chemistry. The objectives of this study were to determine the best correlation between soil-test P and sugarcane crop response in sucrose yield (t sucrose ha^{-1}; TSH) to P fertilizer and to develop a new sugarcane soil-test P calibration for banded P fertilizer application on Histosols in the EAA.

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, 4, and 6 were Pahokee muck soils (euic, hyperthermic Lithic Haplosaprist). Site 3 was a Dania muck soil (euic, hyperthermic, shallow Lithic Haplosaprist). Site 5 was a Lauderhill muck soil (euic, hyperthermic Lithic Haplosaprist). All soils were organic, with <35% mineral content. These soil series are differentiated by depth of the organic soil profile, with the Terra Ceia, Pahokee, Lauderhill, and Dania series having organic soil depths to limestone of >1.30, 0.91–1.30, 0.51–0.91, and <0.51 m, respectively (Rice, Gilbert, and Daroub 2005).

All experimental designs were randomized complete block designs (RCBD) with six, eight, six, five, eight, and eight replications at sites 1, 2, 3, 4, 5, and 6, respectively. Studies at sites 1, 2, 3, 5, and 6 were established at planting, whereas site 4 was initiated with the first ratoon crop. Plots at sites 1–4 were 13.2 m long and plots at sites 5 and 6 were 10.7 m long. Plots at sites 1, 2, 5, and 6 were four rows wide and plots at sites 3 and 4 were six rows wide. All test plots had the commercial standard 1.5-m between-row spacing. Plots were separated by 1.5- to 6.1-m cross and lengthwise fallow alleys, specific for each test. 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 through each plot (sites 1 and 2) or by placing two whole sugarcane stalks side by side in the furrows through each plot and chopping them into similar billet lengths (sites 3–6) to fill the plot length before closing the furrows.

These studies were conducted at different sites in different calendar years, so site and calendar year are confounded (Table 1). Experiments at sites 1–4 each had a single sugarcane cultivar. Cultivar CL 77–797 was grown at site 1, CL 69–886 was grown at site 2, CP 80–1743 was grown at site 3, and CP 89–2143 was grown at site 4. Experiments at sites 5 and 6 included three sugarcane cultivars, CP 72–2086, CP 80–1743, and CP 88–1762, and five P fertilizer rates for a 3 × 5 factorial. Because different cultivars were grown at different sites, cultivar was confounded with site and calendar year in the study, although the interaction of P rate and cultivar was examined at sites 5 and 6. The influence

Table 1
Basic characterization of experiments in phosphorus rate studies with sugarcane on organic soils in Florida

Site	Soil series	Soil pH	Date established[a]	Band/broadcast	P rates[b] (kg P ha^{-1})
1	Terra Ceia	6.6	Nov. 1995	Band	0, 9, 18, 36, 72, 144
2	Pahokee	4.8	Dec. 1995	Band	0, 9, 18, 36, 72, 144
3	Dania	6.2	Nov. 2004	Band	0, 9, 18, 36, 72, 144
4	Pahokee	6.9	Mar. 2007	Band	0, 9, 18, 36, 72, 144
5	Lauderhill	7.3	Nov. 2000	Broadcast	0, 15, 29, 44, 59
6	Pahokee	7.0	Dec. 2000	Broadcast	0, 15, 29, 44, 59

[a]The test at site 4 was established in the first ratoon crop. All other tests were established at planting.

[b]Listed P rates were applied annually for tests at sites 1–4. Tests at sites 5 and 6 received P fertilizer applications only in the plant cane crop.

of calendar year and cultivar was discussed for sites 1–4 by McCray et al. (2010). Irrigation and drainage for all tests were done through field ditches spaced either 120 or 180 m apart. All plots at each test site received normal grower cultural practices with the exception of fertilizer, which was specific for each treatment.

Fertilizer Applications

Phosphorus fertilizer was banded for each annual crop at sites 1–4 at rates of 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 (prior to establishment of the test). At sites 1–4, P rates were selected by multiplying the maximum University of Florida recommended P rate of 36 kg P ha^{-1} by 0, 0.25, 0.5, 1, 2, and 4 to determine these P rates. The 144 kg P ha^{-1} rate was beyond the expected range of yield response and was included specifically to examine the influence of high soil P on sugarcane sucrose concentration (McCray et al. 2010). At sites 5 and 6, P rates of 0, 15, 29, 44, and 59 kg P ha^{-1} were broadcast prior to planting to determine crop response on soils with uniformly elevated soil P concentrations. At these two locations only preplant P applications were made. 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, because N is not specifically recommended for sugarcane growing on organic soils in Florida (Rice, Gilbert, and McCray 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 (K) and micronutrients were applied to all plots at planting based on University of Florida soil-test recommendations for sugarcane (Rice, Gilbert, and McCray 2010). Potassium was applied to all plots in ratoon crops as recommended. The K source for all applications was muriate of potash. Other than specified P broadcast applications, all fertilizer applications were banded in the furrow prior to planting or banded as sidedress applications to the soil surface to the side of each sugarcane row for ratoon crops. Sidedress applications to ratoon crops were made in March to early April each year. For studies using preplant broadcast P applications, fertilizer sources were applied evenly to the soil surface within each plot and incorporated by disking immediately following application. For already-established ratoon crops, band and broadcast applications could not be followed by disking; thus a light between-row cultivation was performed, consistent with routine cultural practices.

Soil Sampling and Analyses

Soil samples were collected in all plots after each sugarcane harvest at all sites (except the last ratoon crop at sites 3, 5, and 6). Soil samples were also collected prior to establishing each test either from control plots (sites 1, 2, 5, and 6) or as composite samples (sites 3 and 4) that represented the overall study site. Soil samples (0–15 cm) were collected in the row at sites 1–4 and between rows at sites 5 and 6. Only zero-P treatments are considered in comparisons of soil P values among sites with band and broadcast treatments, so sample location difference between sites 1–4 and sites 5 and 6 is not expected to be an important factor. Soil samples were placed in aluminum drying pans, air dried in a forced-air drying room at 31 °C, sieved through a 2-mm screen, and equilibrated at 24 °C before analysis. Soil-water pH was determined for all samples (15 cm^3 soil/30 mL water).

Four different soil extraction methods were collectively performed across the six different sites. The water extraction and two different acetic acid extractions are three procedures historically used by the University of Florida Everglades Soil Testing Laboratory to test organic soils, and Bray 2 and Mehlich 3 are extraction procedures that have been successfully used across a wide range of global soils. Additionally, Bray 2 and Mehlich 3 are efficient, performed in a matter of minutes, whereas the water and acetic acid extractions involve overnight soaking of soil in extract solution.

Volumetric soil extractions (sites 3–6) to determine soil P concentrations were performed using four different methods. Acetic acid–extractable P was determined with 0.5 M acetic acid using a 4 cm^3 soil/50 mL extractant ratio. Soil samples were allowed to stand in the extractant overnight and then were shaken for 50 min before filtering for P analysis. Water-extractable P was determined with deionized water using a 4 cm^3 soil/50 mL extractant ratio. Soil samples were allowed to stand in the extractant overnight and then were shaken for 50 min before filtering for P analysis. The Bray 2 extractant [0.03 M ammonium fluoride (NH_4F) and 0.1 M hydrochloric acid (HCl)] was used in a 2.5 cm^3 soil/16 mL extractant ratio. Soil samples were allowed to stand in the extractant for 10 min and then shaken for 5 min before filtering for P analysis. The Mehlich 3 extractant [0.2 M CH_3COOH, 0.25 M ammonium nitrate (NH_4NO_3), 0.015 M NH_4F, 0.013 M nitric acid (HNO_3), and 0.001 M ethylenediaminetetraacetic acid (EDTA)] was used in a 2.5 cm^3 soil/25 mL extractant ratio with a 5-min shaking time immediately after adding the extractant to soil samples. Phosphorus concentrations were determined with a probe colorimeter using the phosphomolybdate blue method (Murphy and Riley 1962). Bray 2 extractions were not performed for samples from sites 5 and 6.

For sites 1 and 2, water and acetic acid extractions were performed volumetrically as described previously. Bray 2–extractable P was performed gravimetrically as described by Andreis and McCray (1998) using a ratio of 2 g of air-dried soil in 16 mL extractant. The gravimetric results were converted to volumetric values using an estimate of air-dried disturbed bulk density for a specific organic-matter content (Andreis and McCray 1998) to convert mg P kg^{-1} to g P m^{-3}. The P-rate experiments at sites 1 and 2 were performed at a time when Bray 2 was of professional interest, and thus soil samples from sites 1 and 2 did not undergo Mehlich 3 extractions. To estimate Mehlich 3–extractable P (M3P) for control plots (zero P) in these two studies, soil samples were collected in a diagonal pattern from both original plot areas in May 2009. These samples were then extracted with the Bray 2 and Mehlich 3 extractions, resulting in a range of paired (Bray 2 and Mehlich 3) extractable P values for soils collected from each location. Relationships between Bray 2–extractable P and M3P for site 1 (Figure 1a) and site 2 (Figure 1b) were developed and used to estimate M3P for plots not receiving P fertilizer based on measured Bray 2–extractable P in those plots.

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 t cane ha^{-1} (TCH). Previous to collecting harvest biomass weights, 16-stalk samples were taken from the two middle rows of each plot for determination of sucrose concentration (KST, kg sucrose t^{-1} cane). Stalk samples were milled and the crusher juice was analyzed for Brix and pol. Brix, which is the percentage of 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,

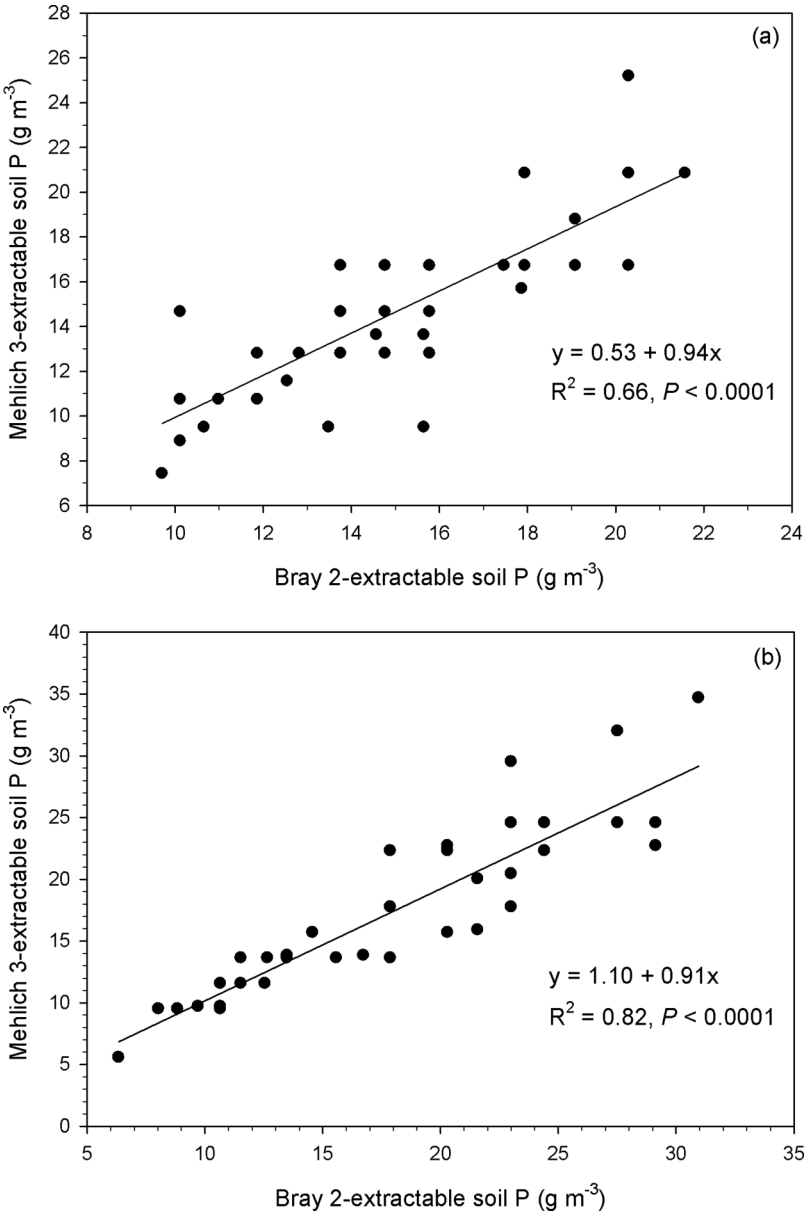

Figure 1. Relationships between Bray 2–extractable P and Mehlich 3–extractable P for (a) site 1 and (b) site 2 using soil samples collected in 2009 from each previous test site.

was measured using a saccharimeter. The KST was determined according to the theoretical recoverable sugar method (Legendre 1992). Tons sucrose ha^{-1} (TSH) was calculated as the product of TCH 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 greatest TSH value for that replication. Relative sucrose ha^{-1} is a relative yield term that allows for comparison of yield response across different years and locations (Evans 1987).

Harvest dates for site 1 were 25–26 February 1997 (plant cane), 6 March 1998 (first ratoon), 18 February 1999 (second ratoon), and 25 March 2000 (third ratoon). Harvest dates for site 2 were 24 January 1997 (plant cane), 6 January 1998 (first ratoon), 27 January 1999 (second ratoon), and 17–18 February 2000 (third ratoon).

Stalk counts and stalk weights were used to calculate TCH at sites 3–6. 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 was analyzed for Brix and pol using a NIR analyzer (model 5000, Foss NIR Systems, Silver Springs, Md.). The KST and TSH calculations were performed as described for sites 1 and 2.

At sites 5 and 6, millable stalks were counted in the two middle rows of each four-row plot in August–September each crop year. A 10-stalk random sample was used to determine TCH. To determine KST, the 10-stalk random sample was milled and the crusher juice was analyzed for Brix and pol as described for sites 1 and 2. Calculation of KST and TSH were also done as described previously.

Stalk weight and KST measurements were performed for site 3 on 19–20 December 2005 (plant cane), 20–21 November 2006 (first ratoon), and 17–18 October 2007 (second ratoon). These measurements were performed for site 4 on 4 December 2007 (first ratoon) and 1 December 2008 (second ratoon). After yield samples were taken, the remaining sugarcane was harvested commercially with machine harvesters. Site 3 plots were harvested on 22 December 2005 (plant cane), 4 December 2006 (first ratoon), and 19 October 2007 (second ratoon). The plant cane crop at site 4 was harvested on 1 March 2007, just prior to establishment of the experiment. After yield samples were taken the following 2 years, site 4 plots were harvested on 17 December 2007 (first ratoon) and 4 February 2009 (second ratoon).

Stalk weight and KST measurements were performed for site 5 on 7 February 2002 (plant cane), 21 January 2003 (first ratoon), and 20 October 2003 (second ratoon). These measurements were performed for site 6 on 28 February 2002 (plant cane), 22 January 2003 (first ratoon), 16 December 2003 (second ratoon), and 28 October 2004 (third ratoon). Site 5 plots were commercially harvested on 28 February 2002 (plant cane), 27 January 2003 (first ratoon), and 23 October 2003 (second ratoon). Site 6 plots were commercially harvested on 9 March 2002 (plant cane), 28 February 2003 (first ratoon), 27 March 2004 (second ratoon), and 15 November 2004 (third ratoon).

Statistical Analyses

All statistical analyses were performed using SAS version 9.2 (SAS Institute 2008). Analysis of variance (ANOVA) 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 (McCray et al. 2010). Analysis of variance was also performed for TCH, TSH, and KST for the plant cane, first ratoon, and second ratoon crops of sites 5 and 6 using the PROC MIXED procedure for a RCBD with site, crop year, cultivar, and P rate treated as fixed effects and replication treated as a random effect to determine effects of site and interactions with site. Because the site × P rate interaction was significant ($P < 0.1$) for all parameters for each of these analyses, ANOVA was performed for TCH, TSH, and KST for each site across

crop years using the PROC GLM procedure for a RCBD with replication, crop year, and P rate (and cultivar for sites 5 and 6) treated as fixed effects. When the interaction of crop year and P rate was significant ($P < 0.1$) for a specific site, a separate ANOVA was performed using the PROC GLM procedure for a RCBD for each crop year with replication and P rate (and cultivar for sites 5 and 6) treated as fixed effects. Determination of TCH or TSH response to P fertilizer for a given site or crop year was based on a probability of 0.05. Linear and quadratic regressions were performed using values for individual plots as appropriate for means across crop years or for individual crop years with significant ($P < 0.05$) TCH or TSH responses to P fertilizer. For sites 1–4, only P rates 0–72 kg P ha^{-1} were used for these regressions because the 144 kg P ha^{-1} rate was included specifically to examine the influence of high soil P on KST (McCray et al. 2010). Required P rate for a specific location and/or crop year was determined using 95% of predicted maximum for the most significant linear or quadratic model. In situations when there was a significant effect of P rate for a given parameter, and linear and quadratic regressions were nonsignificant ($P > 0.05$), 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 all greater rates to determine if there was a significant response to P fertilizer overall. In addition, each P rate > zero was contrasted with the next greatest P rate to determine if doubling the P rate resulted in a significant difference in measured response.

Analysis of variance was performed using PROC GLM with replication and crop year treated as fixed effects to determine the significance of crop year on M3P in the zero-P treatment. Least significant difference was used to compare treatment means. The PROC CORR procedure was used to determine correlations between relative sucrose ha^{-1} and extractable soil P. Nonlinear regression (PROC NLIN) was used to determine best fit in relationships of extractable soil P with relative sucrose ha^{-1}. Selection criteria were significance of the model, maximization of R^2, minimization of residuals, and practicality of the relationship in terms of measured yield responses. Regression models tested were exponential, exponential rise to maximum, quadratic, quadratic plateau, hyperbola, linear plateau, inverse linear, and square root. The model with the best fit was used to determine soil-test categories of very low, low, medium, high, and very high for predicting probability of sugarcane yield response to P fertilizer.

Results and Discussion

Crop Response to P Fertilizer

There were significant ($P < 0.05$) responses in TCH to P fertilizer in 17 of 20 total crop years in the study (Table 2). These included TCH responses across crop years at five of six sites, with a significant TCH response at site 6 only in the third ratoon crop. There were linear reductions in KST at sites 1, 2, and 4 with increasing P rate, but at banded P rates $\leq$ 36 kg P ha^{-1} there was < 5% reduction in KST compared with zero P (McCray et al. 2010). With banded P at sites 1–4, TSH responses to P fertilizer were similar to TCH responses (Table 2). Based on measured yield responses to banded P fertilizer up to 33 kg P ha^{-1} (Table 2), McCray et al. (2010) determined that the maximum P-fertilizer recommendation for Florida Histosols should be maintained at 36 kg P ha^{-1}. The optimum annual banded P rate for sites 1–4 (Table 2) was determined to be consistent across crop years even though P deficiency became more acute with later ratoon crops (McCray et al. 2010).

There was a response in TCH to preplant broadcast P application at sites 5 and 6 (Table 2), but the response at site 6 was limited to the third ratoon crop ($P = 0.002$). There

Table 2
Summary of $P > F$ for fixed effects for P rate and crop year × P rate for t cane ha^{-1} (TCH), t sucrose ha^{-1} (TSH), and kg sucrose t^{-1} cane (KST), crop years with significant ($P < 0.05$) TCH or TSH responses to P fertilizer, and optimum P rate and application method for each test site

	P rate			Crop × P rate			Response years/ total years	Optimum P rate[a]	Application method
Site	TCH	TSH	KST	TCH	TSH	KST			
1	<0.001	<0.001	<0.001	0.292	0.255	0.165	4/4	27 (Q)	Annual band
2	<0.001	<0.001	<0.001	<0.001	<0.001	0.626	4/4	33 (Q)	Annual band
3	0.022	0.079	0.962	0.734	0.761	0.585	3/3	18 (C)	Annual band
4	<0.001	<0.001	<0.001	0.441	0.517	0.007	2/2	33 (Q)	Annual band
5	0.043	0.306	0.142	0.657	0.807	0.557	3/3	44 (C)	Preplant broadcast
6	0.910	0.778	0.122	0.073	0.124	0.921	1/4	39 (L)	Preplant broadcast

[a]Optimum P rate was determined for each location by calculating the minimum P rate required to achieve 95% of maximum TCH or TSH using the most significant model of linear (L) and quadratic (Q) regression. Linear and quadratic regression models were not significant ($P < 0.05$) at sites 3 and 5 so single-degree-of-freedom contrasts were used.

was also a significant response in TSH to P fertilizer in the third ratoon crop at site 6 ($P = 0.003$). There was a significant interactive effect of P rate and cultivar on KST at site 6, but the influence of P rate on TCH and TSH did not differ between cultivars. In some specific crop year × cultivar combinations there was significantly lower KST at greater P rates (data not shown). The specific optimum preplant broadcast P rates for sites 5 and 6 (Table 2) are not useful for the objective of determining appropriate annual banded P rates, but yield responses determined at sites 5 and 6 are useful for determining probability of yield response in relation to soil-test P.

Correlations of Relative Yield and Extractable Soil P

Relationships described by relative yield allow meaningful comparisons across different crop years and locations. Relative sucrose yield comparisons are highlighted because sucrose is by far the most important economic product produced by sugarcane growers. Relationships between relative sucrose ha^{-1} without P fertilizer (zero-P relative sucrose yield) and extractable soil P in samples from the zero-P treatment before each crop year were used to evaluate soil-test P extractants for prediction of sucrose yield response to P fertilizer (Figure 2). Decreasing zero-P relative sucrose yield in these relationships indicates increasing response to P fertilizer. There was a negative correlation between zero-P relative sucrose yield and water-extractable P (Figure 2a). The negative correlation with water-extractable P can be partially attributed to soil-test values ranging from 8 to 12 g P m^{-3} at site 2 (Figure 2a) where there were strong TCH and TSH responses to P fertilizer all four crop years (Table 2). Phosphorus fertilizer is not currently recommended at water-extractable values > 6.6 g P m^{-3} (Gascho and Kidder 1979; Rice, Gilbert, and McCray 2010) and so under the current soil-test calibration, no P fertilizer would have

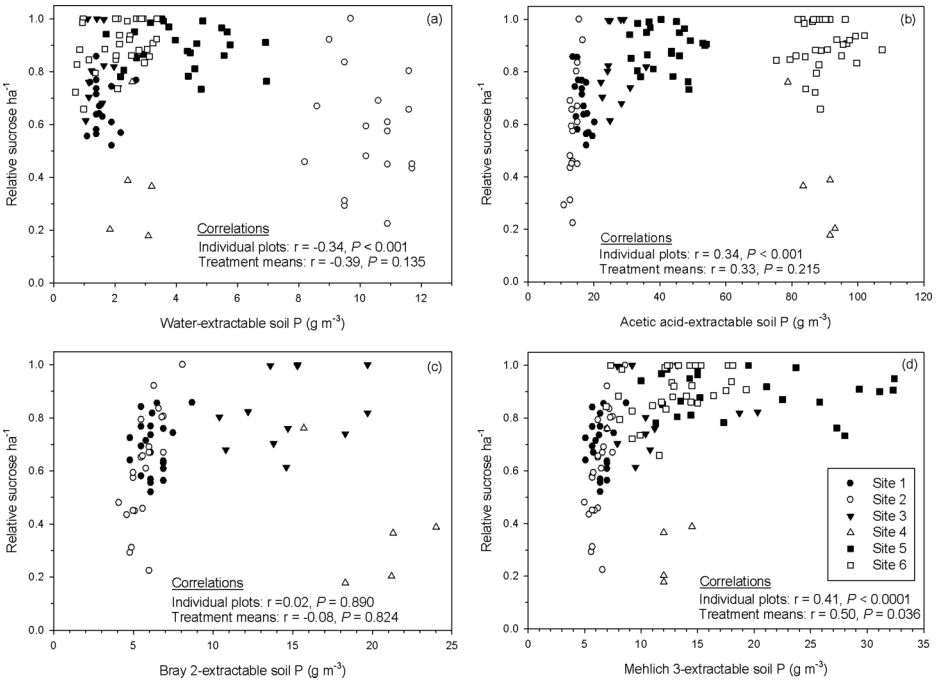

Figure 2. Relationships between precrop (a) water-extractable P, (b) acetic acid–extractable P, (c) Bray 2–extractable P, and (d) Mehlich 3–extractable P for individual zero P plots and zero P relative sucrose ha^{-1}. Zero P relative sucrose ha^{-1} was determined by dividing t sucrose ha^{-1} (TSH) of each zero P plot by the corresponding greatest TSH for all P rates in that replication. The index in panel (d) refers to all four graphs. Bray 2 data were only available for sites 1–4. Mehlich 3 values for sites 1 and 2 are estimates based on linear regressions with Bray 2 P for each site.

been recommended for site 2. The water-extractable P test tends to be undesirably influenced by soil pH; thus elevated water-extractable soil-test values determined at site 2 likely reflect the acidic (pH 4.8) soil properties describing this site (Table 1).

Correlation of zero-P relative sucrose yield and acetic acid–extractable P was positive but not significant for treatment means (Figure 2b). The acetic acid soil test would potentially be a very useful test except for the strong TCH and TSH response at site 4 (Table 2) with pH 6.9 and acetic acid–extractable P values > 80 g P m^{-3} (Figure 2b). Acetic acid was proposed by Korndorfer et al. (1995) as a replacement for water as a soil-test P extractant for Florida sugarcane. The "high" soil-test category proposed by Korndorfer et al. (1995) was >39 g P m^{-3}, which would potentially work with five of the six test sites. However, the acetic acid test would not predict the yield response under the conditions of site 4.

There was not a significant correlation between zero-P relative sucrose yield and Bray 2–extractable soil P (Figure 2c). As with the acetic acid extraction, there were relatively high values for Bray 2–extractable P in the zero-P treatment at site 4, which had strong TCH and TSH responses to P fertilizer (Table 2). Mean Bray 2 P at the beginning of second ratoon at site 4 was 20.1 g P m^{-3} with zero-P relative sucrose yield of 0.38 in that crop.

Mehlich 3 was the only extractant tested that had a significant positive correlation between extractable P and zero-P relative sucrose yield for both individual plots and treatment means (Figure 2d). Zero-P relative sucrose yield values ≤ 0.7 were only determined with M3P < 15 g m^{-3}. Because of the strong positive correlation with relative

yield, Mehlich 3 was selected for further regression analysis in developing a new soil-test P calibration.

Relative Yield Models and Mehlich 3 P

There was an exponential relationship between precrop M3P and zero-P relative sucrose yield using individual zero-P plots from each crop year of each site (Figure 3a). Although this relationship was highly significant, there is substantial variability in relative yield for M3P $\leq$ 15 g P m^{-3}. Some of this may be explained by variation in mineralization rates with differences in soil moisture and cycles of flooding and draining (Diaz, Anderson, and Hanlon 1993). Water table depths and previous flood-drainage history influence P release from organic soils and the labile fraction of soil P (Martin et al. 1997). While the Mehlich 3 extractant was chosen for a consistent relationship with crop P availability, factors that influence P sorption in EAA soils, including mineral content, pH, total calcium (Ca), total iron (Fe), and free carbonates (Porter and Sanchez 1992), may also explain some variability in relationships between M3P and relative yield (Figure 3a).

Nonlinear regression was also performed using mean and minimum relative sucrose yield calculated across replications, crop years, and sites for each 1 g P m^{-3} increment of M3P (Figures 3b and 3c). Mean relative sucrose yield reached 99% of maximum for the exponential model at M3P of approximately 19 g P m^{-3} (Figure 3b), indicating that probability of response to P fertilizer increases as M3P is decreased from 19 g P m^{-3}. Relative sucrose yield ranged as low as 0.22 (22%) at site 2 and as low as 0.18 at site 4 (Figure 3a). While there were some instances when relative yield for a given M3P value was measured at 1.00 with M3P $\geq$ 7 g P m^{-3} (individual points in Figure 3a), there were also minimum relative yield values $<$ 0.50 with M3P $\leq$ 15 g P m^{-3} (Figure 3c). The relationship of minimum relative sucrose with M3P is useful for ensuring that adequate P is available across the range of growing conditions in EAA soils. Minimum relative sucrose yield reached a plateau at M3P of approximately 25 g P m^{-3} (Figure 3c). This indicates that there should be a low probability of sugarcane yield response to P fertilizer at M3P $>$ 25 g P m^{-3}, although there was a significant response in TCH to P fertilizer application at site 5 (Table 2) with a preplant M3P value of 28.7 g P m^{-3} (Table 3). Also, though M3P values without P fertilizer application were all less than 35 g P m^{-3} (Figure 3a), there was no yield response when M3P values were increased to over 100 g P m^{-3} in the banded row (Figure 4).

Decline in relative yield in successive crops may be attributable to a decline in soil-test P or increasing crop age or both. For plant cane through third ratoon crops, the intercept was successively lower and the slope was successively greater with increasing crop age for relationships between M3P and zero-P relative sucrose ha^{-1} (Figure 5). These linear regressions suggest that yield response becomes steeper in older crops as M3P values decline. The linear regressions are specific for the test sites in this study and are useful for showing the trend with crop age but are not applicable for predicting yield response for other soils for a given crop year.

A decline in soil-test P over time as determined at sites 5 and 6 ($P < 0.001$) in the zero-P treatment (Table 3) may result in an increased yield response in successive crops as measured at site 6 where there were significant TCH and TSH responses to P fertilizer only in the third ratoon crop (Table 2). Although M3P declined over time at site 5, there was a response in TCH across crop years (Table 2). Some variation in relative yield at a specific M3P value may be explained by crop year, with successively older ratoon crops having lower relative yields as compared with earlier crops. There were steeper TCH and TSH response curves in later ratoon crops as compared to earlier crops at site 2 (significant

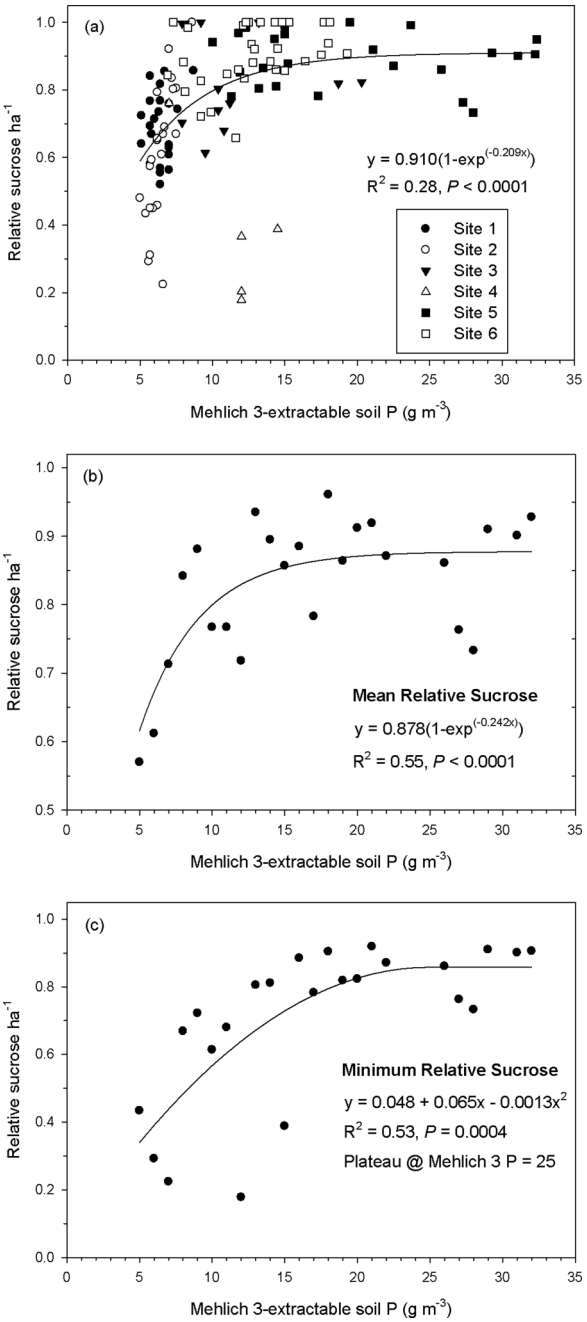

Figure 3. Relationships between precrop Mehlich 3–extractable P and zero P relative sucrose ha^{-1} for (a) individual zero P plots, (b) mean relative sucrose, and (c) minimum relative sucrose. Zero P relative sucrose ha^{-1} for individual plots was determined by dividing t sucrose ha^{-1} (TSH) of each zero P plot by the corresponding greatest TSH for all P rates in that replication. Relative sucrose ha^{-1} values for panels (b) and (c) are the mean and minimum values of each Mehlich 3 P increment of 1 g P m^{-3} of data in panel (a). Mehlich 3 P values for sites 1 and 2 are estimates based on linear regressions with Bray 2 P for each site.

Table 3
Precrop Mehlich 3–extractable soil P without P fertilizer (before test establishment or at the beginning of each crop) for all test sites

Crop year	Site 1[a]	Site 2[a]	Site 3	Site 4	Site 5	Site 6
			Mehlich 3–extractable soil P (g m^{-3})			
Plant cane	5.7	6.9	—	—	28.7	15.0
First ratoon	6.5	7.2	10.3	14.4[b]	17.1	14.5
Second ratoon	6.4	6.1	12.7	11.5	12.7	13.3
Third ratoon	6.8	5.6	—	—	—	8.6
$P > F$	0.103	0.028	0.244	—	<0.001	<0.001
LSD (0.05)	1.0	1.1	4.7	—	3.1	1.5

[a]Mehlich 3–extractable P values for sites 1 and 2 were estimated based on linear regressions with Bray 2–extractable P for each site.
[b]All values are means for the zero-P treatment except the value before the first ratoon crop at site 4, which was from a composite sample.

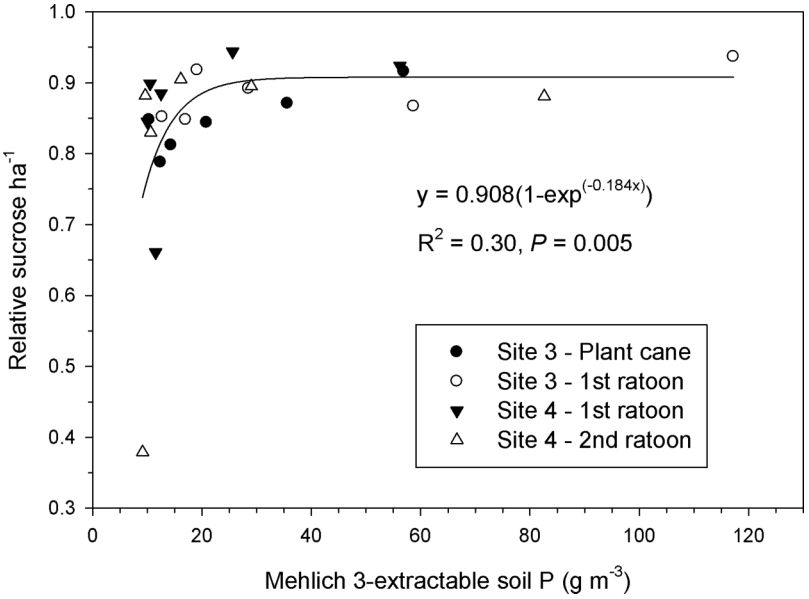

Figure 4. Relationship between postcrop Mehlich 3–extractable P means and relative sucrose ha^{-1} means for all P rates (0, 9, 18, 36, 72, and 144 kg P ha^{-1} banded annually) in two crops at sites 3 and 4. Relative sucrose ha^{-1} was determined by dividing t sucrose ha^{-1} (TSH) of each plot by the corresponding greatest TSH for all P rates in that replication.

crop × P rate interaction, Table 2), but P fertilizer requirement did not change across crop years (McCray et al. 2010). At site 2, M3P was extremely low in all crop years with slightly lower M3P in the first and second ratoon crops (Table 3). The steeper response curves in later ratoon crops at site 2 are largely attributable to crop age. This may be explained by reduced growth and vigor of the ratoon crop root system (Humbert 1959).

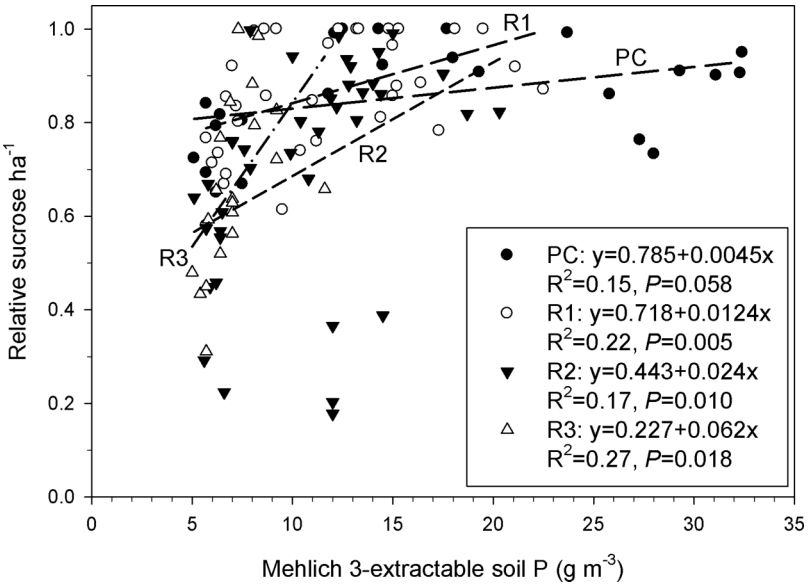

Figure 5. Linear relationships between Mehlich 3–extractable P and zero P relative sucrose ha^{-1} for plant cane (PC), first ratoon (R1), second ratoon (R2), and third ratoon (R3) crops using data for individual zero-P plots. Zero-P relative sucrose ha^{-1} was determined by dividing t sucrose ha^{-1} (TSH) of each zero-P plot by the corresponding greatest TSH for all P rates in that replication. Mehlich 3 P values for sites 1 and 2 are estimates based on linear regressions with Bray 2 P for each site.

Proposed Calibration using Mehlich 3

Relationships between M3P and relative sucrose ha^{-1} (Figures 3a, 3b, and 3c) were used to develop a proposed new soil-test P calibration (Table 4). Mean relative sucrose yield was reduced at M3P < 19 g P m^{-3}, with mean relative yield < 0.80 with M3P < 10 g P m^{-3} (Figure 3b). Minimum relative sucrose yield reached a plateau with M3P $\geq$ 25 g P m^{-3} (Figure 3c). The greatest precrop M3P value corresponding to a yield response to P fertilizer (Table 2) was 28.7 g P m^{-3} (Table 4). Although this response was only significant for TCH, the response was significant across crop years and the response of TSH to P fertilizer has generally closely followed that of TCH (McCray et al. 2010). An M3P value

Table 4
Proposed P fertilizer calibration based on the Mehlich 3 extractant for sugarcane growing on Florida organic soils

Mehlich 3 P (g P m^{-3})	Banded P rate (kg P ha^{-1})
≤10	36
11–15	30
16–20	24
21–25	18
26–30	9
>30	0

of 30 g P m^{-3} was chosen, above which there would be little probability of yield response to P fertilizer (Table 4). Zero-P plots with M3P values $\leq$ 10 g P m^{-3} had a high percentage (77%) with relative sucrose < 0.80 and so these M3P values were used as the lowest soil-test category in the calibration. Mehlich 3–extractable P values of 11–30 g P m^{-3} were divided into four equally spaced soil-test categories, with a total of six categories based on probability of response to P fertilizer (Table 4). The current lowest recommended P rate is 19.6 kg P ha^{-1} (Gascho and Kidder 1979; Rice, Gilbert, and McCray 2010), which is similar to the 18 kg P ha^{-1} rate assigned to the 21–25 g P m^{-3} soil-test category (Table 4). A very low rate of approximately half the lowest current P rate (9 kg P ha^{-1}) is assigned to the 26–30 g P m^{-3} soil-test category (Table 4). This is slightly higher than the M3P plateau determined for minimum relative sucrose yield (Figure 3c) but will allow for a possible yield response as measured at site 5 (Table 2) with a precrop M3P of 28.7 g P m^{-3} (Table 3).

A maximum recommended banded P fertilizer rate for sugarcane was set at 36 kg P ha^{-1} (Table 4) based on the results of banded applications in this study (McCray et al. 2010) and previous work (Andreis and McCray 1998). Banding P fertilizer on sugarcane in the EAA is a BMP intended to reduce P application rates and subsequent P discharge (Lang et al. 2006). Annual P fertilizer requirement at sites 1, 2, 3, and 4 were determined to be 27, 33, 18, and 33 kg P ha^{-1} (Table 2), and using the proposed calibration these sites would receive annual P applications of 36, 36, 30, and 30 kg P ha^{-1} (Tables 3 and 4), respectively. Annual P fertilizer requirement has been determined to be similar across years at sites 1–4 (McCray, Gilbert, and McCray 2010) even with steeper response in older crops in situations with similar soil-test P across years (Table 3). The greater P removal that occurs with generally greater TCH and TSH of plant cane compared to later crops may be offset by the relatively stronger root system of plant cane (Humbert 1959) so that P fertilizer requirement is consistent across years. Because M3P declined in ratoon crops at sites 5 and 6 (Table 3), greater P rates would be recommended with lower soil-test P in older crops. This can be done if soil samples are collected for each crop year. However, because of the difficulty in obtaining representative soil samples on which to base ratoon crop fertilizer recommendations after banding P fertilizer, current recommendations for plant cane and ratoon crops are based on preplant soil samples (Gascho and Kidder 1979; Rice, Gilbert, and McCray 2010). If this approach is continued, there will need to be consideration in ratoon crop recommendations for possible decline in soil-test values over time.

Conclusions

A new soil-test P fertilizer calibration for sugarcane on Florida organic soils is proposed based on the Mehlich 3 extraction. This calibration is based on the analysis of six different P-rate test sites in which crop response (TCH or TSH) to P fertilizer was determined in 17 of 20 crop years. The greatest recommended banded P rate is 36 kg P ha^{-1} with M3P $\leq$ 10 g P m^{-3} and no P fertilizer is recommended with M3P $>$ 30 g P m^{-3}.

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