Soil Phosphorus Forms Related to Extractable Phosphorus in the Everglades Agricultural Area

James Mabry McCray, Alan L. Wright, Yigang Luo, and Shangning Ji

Abstract: Optimizing P fertilizer recommendations with proper soil testing will reduce overapplication and is vital for reducing P discharge into the Everglades. Soil samples from five Histosols in the Everglades Agricultural Area were analyzed with the objectives of (i) quantifying the forms of soil P and (ii) relating extractable P using water, acetic acid, Bray 2, and Mehlich 3 extractants to these P fractions. The percentages of five P fractions generally increased with increasing recalcitrance in the order of labile P (KCl-P*i*), Fe-Al–bound P (NaOH-P*i*), humic-fulvic–bound P (NaOH-P*o*), Ca-Mg–bound P (HCl-P*i*), and residual P with the exceptions of two acid soils in which the highest percentage of total P was in the humic-fulvic fraction. Water-extractable P was strongly ($P < 0.001$, $r = 0.97$) correlated with labile P, with each measuring greater P with decreasing pH. Acetic acid–extractable P was correlated ($P < 0.05$) with residual P ($r = 0.47$) and negatively correlated with Fe-Al–bound P ($r = -0.53$). This suggests that this extractant recovers more recalcitrant forms of soil P associated with residual P yet is unable to remove P associated with hydroxides of Fe and Al. Bray 2–extractable P included labile P, humic-fulvic P, and some residual P, with possible contribution from Fe-Al–bound P. Mehlich 3 was the only extractant tested that included labile and nonlabile (primarily Fe-Al–bound) P while excluding residual P, thus deemed to best indicate the plant-available P pool.

Key words: Everglades agricultural area, Histosol, phosphorus fractions, soil testing, sugarcane.

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Histosols are the predominate soils of the Everglades Agricultural Area (EAA) of south Florida. The EAA, an area of 280,000 ha located south and east of Lake Okeechobee, was drained in the early 1900s for conversion to agriculture. Phosphorus in drainage water from the EAA is an environmental concern because the Everglades are historically P limited. Increased P concentrations have been found to accelerate eutrophication of Everglades wetlands (Bottcher et al., 1995; Wright and Reddy, 2008), resulting 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 that annual P loads be reduced by at least 25% relative to historic baseline trends documented in 1978–1988 basin drainage data (Whalen and Whalen, 1994). Soil testing for crop P availability is an important best management practice that growers use to meet the P load reduction requirements (Daroub et al., 2005) by optimizing fertilizer use to meet the crop needs while minimizing the potential for overapplication.

Sugarcane (*Saccharum* spp.) is grown on 157,000 ha in south Florida, with approximately 80% of this hectarage on organic soils of the EAA (Rice et al., 2009). Water-extractable P is currently used by the Everglades Soil Testing Laboratory (University of Florida) to make P fertilizer recommendations for sugarcane (Gascho and Kidder, 1979; Gilbert and Rice, 2009). Water-extractable P was a soil test developed primarily for fertilizer recommendations for vegetables (Forsee, 1950), which have a much shorter growing season than sugarcane. However, Korndorfer et al. (1995) compared water, Mehlich 1, and 0.5 *M* acetic acid 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. Research with vegetables on organic soils in Florida has suggested that the Mehlich 3 extractant performs satisfactorily for P extraction over a wider pH range than water (Hochmuth et al., 2009), and Mehlich 3 could also be used for extraction of other nutrients (Mehlich, 1984).

Water-extractable P is designed to be a measure of labile P (Castillo and Wright, 2008). The interest in extractants other than water exists because for long-term crops such as sugarcane, other slowly available forms of soil P should be included in a soil test to properly relate to crop availability (Glaz et al., 2000; Korndorfer et al., 1995). Castillo and Wright (2008) determined that a cultivated EAA Histosol (pH 6.8) had 48% of total P in inorganic fractions, with 12% and 36% of total P being bound by Fe and Al, and by Ca, respectively. Oxidation of organic matter, which occurs with soil subsidence, increases inorganic P (Reddy et al., 1998). Ivanoff et al. (1998) determined that 18%, 11%, and 13% of total P were associated with fulvic acid and humic acid or were remaining as residual organic P, respectively, in a cultivated EAA Histosol with pH 5.1. The dominant P fractions for long-term P storage are organic P and P associated with Ca and Mg (Reddy et al., 1998).

Sugarcane yield responses to P fertilizer have been determined in EAA soils with low P availability (Andreis and McCray, 1998; Glaz et al., 2000; McCray et al., 2010). Determination of soil P fractions removed by soil extractants can provide information to assist in selection of an appropriate soil-test method. The objectives of this study were to (i) quantify the forms of soil P in five soils from the EAA and (ii) relate extractable P using four P extractants (water, 0.5 *M* acetic acid, Bray 2, and Mehlich 3) to these P fractions.

MATERIALS AND METHODS

Soil Characterization and P Fractionation

Air-dry soil samples (0- to 15-cm depth) from five P fertilizer rate test sites were selected for analysis. For Sites 3 to 5, four soil samples from zero P treatment plots were selected from each site. Because experimental soil samples from Sites 1 and 2 were no longer available, four soil samples per site were selected

Everglades Research and Education Center, University of Florida, 3200 E. Palm Beach Rd., Belle Glade, FL 33430. Dr. James Mabry McCray is corresponding author. E-mail: jmmccray@ufl.edu
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from transect soil samples collected from each of these sites in 2009. The P rate experiments were conducted from 1995 to 2000 at Sites 1 and 2, from 2004 to 2007 at Site 3, from 2007 to 2009 at Site 4, and from 2004 to 2006 at Site 5. Commercial sugarcane was grown at Sites 1 and 2 following the P rate experiments at those sites. Phosphorus fertilizer sources used commercially or experimentally at all locations were either triple superphosphate or monoammonium phosphate.

All sites were located in the EAA of south Florida. Site 1 was a Terra Ceia muck soil (euic, hyperthermic Typic Haplosaprist). Sites 2 and 4 were Pahokee muck soils (euic, hyperthermic Lithic Haplosaprist). Sites 3 and 5 were Dania muck soils (euic, hyperthermic, shallow Lithic Haplosaprist). All soils were organic with less than 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).

After collection, all soil samples were placed in aluminum drying pans, air dried in a forced-air drying room at 31°C, and sieved (without grinding) through a 2-mm screen. Soil pH was determined with a combination electrode in a 1:2 vol/vol suspension of air-dried soil in deionized water after a 1-h equilibration time. All P fractions and total nutrient determinations were conducted on samples that were dried at 70°C for 24 h after being air dried. Soil densities were determined by weighing soil measured in a volumetric scoop after air drying and oven drying. Total organic C was determined by loss-on-ignition at 550°C for 4 h after conversion to organic C using a factor of 0.51. The distribution of P in soil was determined using a modification of a sequential chemical fractionation procedure (Hedley et al., 1982; Ivanoff et al., 1998; Reddy et al., 1998). Approximately 1 g soil was extracted with 25 mL of 1 *M* KCl for 1 h, passed through 0.45-μm filters, and analyzed for KCL-P*i* (labile P). The remaining sample was extracted with 25 mL of 0.1 *N* NaOH for 17 h and analyzed for NaOH-P*i* (Fe-Al–bound P), followed by the extraction of the remaining sample with 25 mL of 0.5 *N* HCl for 24 h and analysis of HCl-P*i* (Ca-Mg–bound P). The remaining sample was digested with 6 *N* HCl for 1 h at 150°C and analyzed for residual P. The humic-fulvic acid fraction (NaOH-P*o*) was determined after digestion of 5 mL of the 0.1 *N* NaOH extract with 11 *N* H_2SO_4 for 4 h at 350°C (NaOH-TP) and subtraction of the NaOH-P*i* from the NaOH-TP. The P content of extracts was measured using the ascorbic acid–molybdenum blue method (Murphy and Riley, 1962) with an AQ2+ discrete analyzer (Seal Analytical Inc., Mequon, WI).

A duplicate sample of the original soil was ashed at 550°C for 4 h, then extracted with 6 *N* HCl and analyzed for total P, Ca, Mg, Fe, and Al. Phosphorus concentrations were measured as described above. Calcium, Mg, Fe, and Al digest concentrations were determined using inductively coupled argon plasma spectrometry.

Soil P Extractions

Volumetric soil extractions 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 (Korndorfer et al., 1995). 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 (Korndorfer et al., 1995). 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 (Bray and Kurtz, 1945) (0.03 *M* NH_4F and 0.1 *M* HCl) was used in a 2.5 cm^3 soil/16 mL extractant ratio. Soil

TABLE 1. Selected Physical and Chemical Characteristics of Soil (0- to 15-cm Depth, n = 4) From Five Sites of a P Fertilizer Rate Study on Florida Histosols

Parameter	Site 1		Site 2		Site 3		Site 4		Site 5	
pH	6.9	(0.2)[†]	5.3	(0.5)	6.2	(0.2)	6.9	(0.2)	6.1	(0.3)
Organic C, g kg^{-1}	391	(12)	419	(32)	425	(3)	403	(8)	430	(5)
Air-dry soil density, g cm^{-3}	0.81	(0.05)	0.76	(0.05)	0.88	(0.05)	0.74	(0.02)	0.96	(0.02)
Oven-dry soil density, g cm^{-3}	0.69	(0.05)	0.66	(0.05)	0.72	(0.05)	0.61	(0.02)	0.80	(0.01)
Extractable P (g m^{-3})										
Water	0.9	(0.2)	9.8	(3.4)	1.3	(0.5)	2.7	(0.6)	1.7	(0.3)
Acetic acid	21.7	(1.8)	30.9	(2.8)	26.5	(3.9)	86.7	(6.8)	25.3	(5.8)
Bray 2	11.1	(1.0)	21.2	(4.9)	15.9	(1.7)	19.3	(2.3)	23.7	(4.6)
Mehlich 3	10.4	(2.2)	19.1	(5.2)	10.7	(2.1)	10.7	(2.5)	19.2	(2.4)
P fractions (g m^{-3})										
Labile (KCl-P*i*)	2.1	(0.6)	11.4	(3.8)	4.1	(0.8)	4.9	(0.6)	4.1	(0.6)
Fe-Al (NaOH-P*i*)	40	(15)	44	(7)	50	(10)	19	(1)	109	(4)
Humic-fulvic (NaOH-P*o*)	46	(52)	147	(107)	93	(123)	87	(62)	388	(79)
Ca-Mg (HCl-P*i*)	172	(110)	47	(29)	216	(47)	231	(34)	195	(45)
Residual P	237	(39)	101	(21)	214	(24)	293	(43)	251	(32)
Total P	567	(86)	352	(59)	660	(98)	746	(59)	944	(80)
P fractions/total P (% efficiency)	87	(15)	98	(30)	87	(14)	85	(7)	101	(11)
Total metals (g m^{-3})										
Ca	34,725	(2,592)	21,585	(3,353)	36,379	(1,508)	32,021	(2,456)	38,409	(2,404)
Mg	2,758	(388)	911	(130)	1,578	(69)	2,260	(246)	4,104	(593)
Fe	7,256	(1,046)	3,686	(292)	6,739	(511)	2,678	(208)	11,177	(515)
Al	5,429	(900)	1,908	(417)	2,107	(208)	1,364	(101)	6,850	(568)

[†]Mean value with S.D. in parentheses.

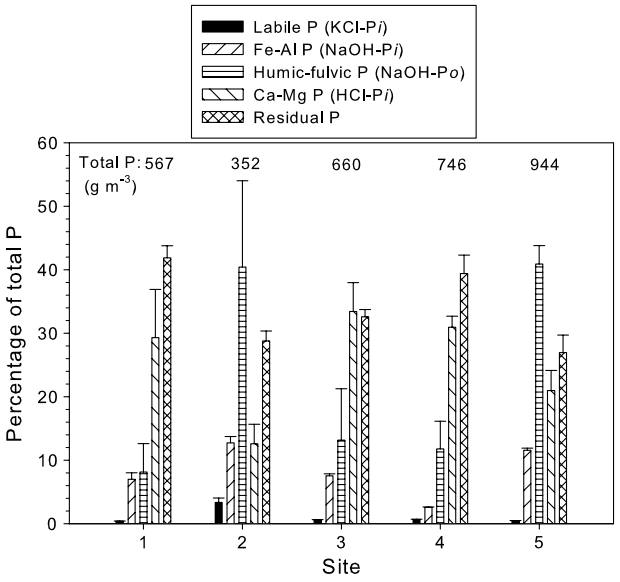

FIG. 1. Soil P fractions as percentages of total soil P at five sites on Histosols soils in Florida. Bars represent S.E. of the sample means.

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* acetic acid, 0.25 *M* NH_4NO_3, 0.015 *M* NH_4F, 0.013 *M* HNO_3, and 0.001 *M* EDTA) was used in a 2.5 cm^3 soil/25 mL extractant ratio with a 5-minute shaking time immediately after adding the extractant to soil samples, then filtered for P analysis (Mehlich, 1984). Phosphorus concentrations were measured using the ascorbic acid–molybdenum blue method (Murphy and Riley, 1962) using a probe colorimeter.

Statistical Analysis

All statistical analyses were performed using SAS version 9.2 (SAS Institute, 2008). Correlations between soil parameters were determined with the PROC CORR procedure. Multiple regression equations were calculated using PROC REG to predict extractable P for each of the four extractants using the various P fractions. Forward regression was used to determine equations with variables considered only for model entry at $P = 0.50$. Final regression models for each extractant were selected using the model for the last step in which all variables were significant at $P = 0.05$. Linear regression (PROC GLM) was used to relate extractable P to the various P fractions and to relate extractable P and each P fraction to soil pH.

RESULTS AND DISCUSSION

Distribution of P Fractions

Total P was lowest at Site 2, with only 37% of the total P at Site 5 (Table 1), indicating the substantial variability in total P in EAA soils. Labile P was a small percentage of total P at all sites (average, 1.1%), with the highest percentage at Site 2 (Fig. 1), which also had the lowest pH of all sites (Table 1). The Fe-Al–bound P fraction was the second smallest in percentage of total P for all sites. There was a large range in total Fe among sites, with Site 5 having approximately four times as much total Fe as Site 4 (Table 1). Site 4 also had the lowest value for Fe-Al–bound P. The humic-fulvic P fraction constituted more than 40% of total P at Sites 2 and 5, but substantially lower percentages at the other locations (Fig. 1). Castillo and Wright (2008) attributed increased humic-fulvic–bound P in an uncultivated EAA soil to relatively low pH compared with a cultivated soil. The slight to moderate acidity at Sites 2 and 5 (pH 5.3 and 6.1, respectively) may also account for the relatively high percentage of P in the humic-fulvic fraction, even though Site 5 had relatively high total Ca (Table 1). The Ca-Mg–bound P fraction constituted greater than 29% of total P at Sites 1, 3, and 4 (Fig. 1), with two of these sites having pH near 7.0. Soils in the EAA are generally becoming shallower because of subsidence (Shih et al., 1998; Wright and Snyder, 2009), which has resulted in increases in pH and incorporation of more Ca from underlying limestone (Sanchez and Porter, 1994; Snyder, 1994; Wright, 2009). These changes can result in a high proportion of soil P being bound in the Ca-Mg fraction. Residual P constituted a substantial percentage of total P at each site, ranging from 27% to 42% (Fig. 1). The percentages of the five P fractions generally increased with

TABLE 2. Correlations of Extractable Soil P (0–15 cm) With Soil pH, Total Organic C, and P Fractions for Five Florida Histosols (n = 20)

	Extractable P			
Parameter	**Water**	**Acetic Acid**	**Bray 2**	**Mehlich 3**
	r			
pH	−0.79**	0.39	−0.44	−0.64**
Organic C	0.34	−0.21	0.53*	0.48*
Labile P(KCl-P*i*)	0.97***	0.06	0.54*	0.63**
Fe-Al P(NaOH-P*i*)	−0.14	−0.53*	0.47*	0.56*
Humic-fulvic P (NaOH-P*o*)	−0.08	−0.21	0.54*	0.49*
Ca-Mg P (HCl-P*i*)	−0.68***	0.33	−0.08	−0.40
Residual P	−0.76***	0.47*	−0.07	−0.40
Total P	−0.64**	0.18	0.26	<0.01
Water-extractable P	—	0.02	0.43	0.58**
Acetic acid–extractable P	0.02	—	0.22	−0.23
Bray 2–extractable P	0.43	0.22	—	0.76***

*Significant correlation at $P = 0.05$.

**Significant correlation at $P = 0.01$.

***Significant correlation at $P = 0.001$.

increasing recalcitrance in the order of labile P, Fe-Al–bound P, humic-fulvic–bound P, Ca-Mg–bound P, and residual P, with the exceptions of Sites 2 and 5 at which the highest percentage of total P was in the humic-fulvic fraction (Table 1).

Extractable P and P Fractions

Water-extractable P (water P) was negatively related to Ca-Mg–bound P ($r = -0.68$), residual P ($r = -0.76$), and total P ($r = -0.64$) (Table 2, Fig. 2). Water P was positively correlated with labile P ($r = 0.97$) (Table 2), and labile P was the only P fraction with a positive relationship with water P in multiple regressions (Table 3). Water P was not significantly correlated with Fe-Al–bound P or humic-fulvic–bound P (Table 2). Water P and labile P were each negatively related to pH (Table 2, Fig. 3), with water P being substantially higher at Site 2, which had pH near 5 (Table 1). There have been concerns that the water soil test P method may be too sensitive to pH (McCray et al., 2010). Water-extractable P is closely

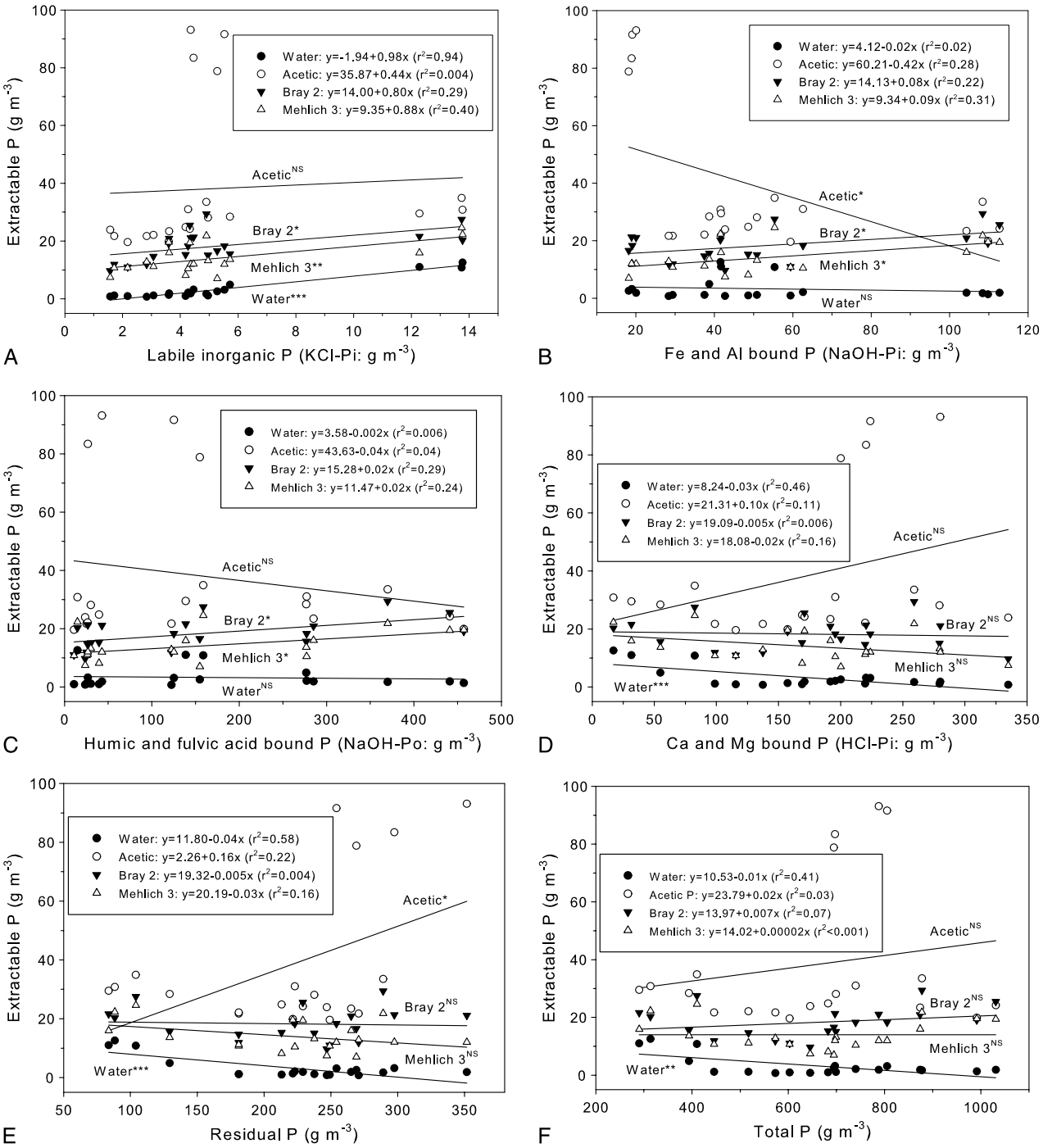

FIG. 2. Relationships between (A-E) soil P fractions or (F) total soil P and extractable soil P for the five Histosols in the study. Significant regressions determined at P = *0.05, **0.01, and ***0.001, respectively. Nonsignificant (NS) regressions determined at $P = 0.05$.

TABLE 3. Regression Equations Relating Soil Extractable P to Soil P Fractions in Five Florida Histosols[†]

Water

Step 1			Step 2			Step 3			Step 4		
Variable	***P*>F**	**R^2**	**Variable**	***P*>F**	**R^2**	**Variable**	***P*>F**	**R^2**	**Variable**	***P*>F**	**R^2**
Labile P	<0.0001	0.94	Ca-Mg P	0.0189	0.96	Humic-fulvic P	0.2109	0.96	Residual P	0.4168	0.96

Final model[‡]: Water P = −0.23 + 0.88 (labile P)*** − 0.007 (Ca-Mg P)* (R^2 = 0.96)

Acetic Acid

Step 1			Step 2			Step 3			Step 4		
Variable	***P*>F**	**R^2**	**Variable**	***P*>F**	**R^2**	**Variable**	***P*>F**	**R^2**	**Variable**	***P*>F**	**R^2**
Fe-Al P	0.0173	0.28	Residual P	0.0117	0.51	Labile P	0.0010	0.75	Humic-fulvic P	0.0226	0.83

Final model: Acetic acid P = −34.59 + 4.61 (labile P)*** − 0.67 (Fe-Al P)*** + 0.08 (humic-fulvic P)* + 0.33 (residual P)*** (R^2 = 0.83)

Bray 2

Step 1			Step 2			Step 3			Step 4		
Variable	***P*>F**	**R^2**	**Variable**	***P*>F**	**R^2**	**Variable**	***P*>F**	**R^2**	**Variable**	***P*>F**	**R^2**
Labile P	0.0140	0.29	Humic-fulvic P	0.0023	0.60	Residual P	0.0025	0.78	Fe-Al P	0.1706	0.80

Final model: Bray 2 P = −2.05 + 1.43 (labile P)*** + 0.02 (humic-fulvic P)*** + 0.04 (residual P)** (R^2 = 0.78)

Mehlich 3

Step 1			Step 2			Step 3			Step 4		
Variable	***P*>F**	**R^2**	**Variable**	***P*>F**	**R^2**	**Variable**	***P*>F**	**R^2**	**Variable**	***P*>F**	**R^2**
Labile P	0.0030	0.40	Fe-Al P	<0.0001	0.77	Residual P	0.4921	0.78	Ca-Mg P	0.4249	0.79

Final model: Mehlich 3 P = 3.81 + 0.95 (labile P)*** + 0.10 (Fe-Al P)*** (R^2 = 0.77)

*Regression term was significant at P = 0.05

**Regression term was significant at P = 0.01.

***Regression term was significant at P = 0.001.

[†]Forward regression was used to determine equations with variables only considered for model entry at P = 0.50. P>F values are given for significance of each variable added to the model, and model R^2 values are given at each step. All units are in g P m^{-3}.

[‡]Final models for each extractant were selected by using the model for the last step in which all variables were significant at P = 0.05. Fractions considered were KCl-Pi (labile P), NaOH-Pi (Fe-Al P), NaOH-P*o* (humic-fulvic P), HCl-Pi (Ca-Mg P), and residual P.

related to the extraction with KCl, which represents the labile P fraction.

Acetic acid–extractable P (acetic P) was positively related to residual P (r = 0.47) and negatively related to Fe-Al–bound P (r = −0.53) (Table 2, Fig. 2), indicating that the extractant was able to recover some of the more recalcitrant P but was not able to remove P associated with hydroxides of Fe and Al. Correlations of acetic P with labile P, humic-fulvic–bound P, Ca-Mg–bound P, and total P were insignificant (Table 2). Acetic P is the only P extraction that did not have a significant positive correlation with labile P, probably because of the relatively high acetic P values at Site 4 (Table 1), which may have prevented a significant linear relationship (Fig. 2A). Labile P was inversely related to pH (r^2 = 0.66), and acetic P had a positive but insignificant relationship with pH (r^2 = 0.15) (Fig. 3). At Site 4, labile P would have had only a minor contribution to acetic P because pH was relatively high (pH 6.9), but as indicated by multiple regression, labile P did make a significant contribution to acetic P across sites (Table 3). Regression also indicated that the humic-fulvic–bound P and residual P fractions also contribute significantly to acetic P (Table 3). It is not clear why acetic acid would remove more of the residual P fraction than the Ca-Mg–bound P fraction. In these organic soils, there was a large percentage of P in the residual P fraction (Fig. 1), some of which may be extracted by acetic acid during the very long extraction time (20 h).

Bray 2–extractable P (Bray 2 P) was positively related to labile P (r = 0.54), Fe-Al–bound P (r = 0.47), and humic-fulvic–bound P (r = 0.54) (Table 2, Fig. 2). Bray 2 P was not significantly correlated with Ca-Mg–bound P, residual P, or total P (Table 2). Multiple regressions indicated that labile P, humic-fulvic–bound P, and residual P were positively related to Bray 2–extractable P (Table 3). Although Fe-Al–bound P was significantly correlated with Bray 2 P (r = 0.47), it did not add significantly to the regression model. Residual P was not significantly correlated with Bray 2 P (r = −0.07), but significantly improved the regression model. This suggests that the Bray 2 extractant was able to remove a small amount of residual P, although not consistently across all soils as indicated by the poor correlation. Bray 2 P was not significantly related to pH, although the correlation was negative (r = −0.44, P = 0.053) (Table 2, Fig. 3A). The P fractions extracted by Bray 2 primarily included labile P and humic-fulvic–bound P with some contribution from residual P and also possible contribution from Fe-Al–bound P.

Mehlich 3–extractable P (Mehlich 3 P) was positively related to labile P (r = 0.63), Fe-Al–bound P (r = 0.56), and

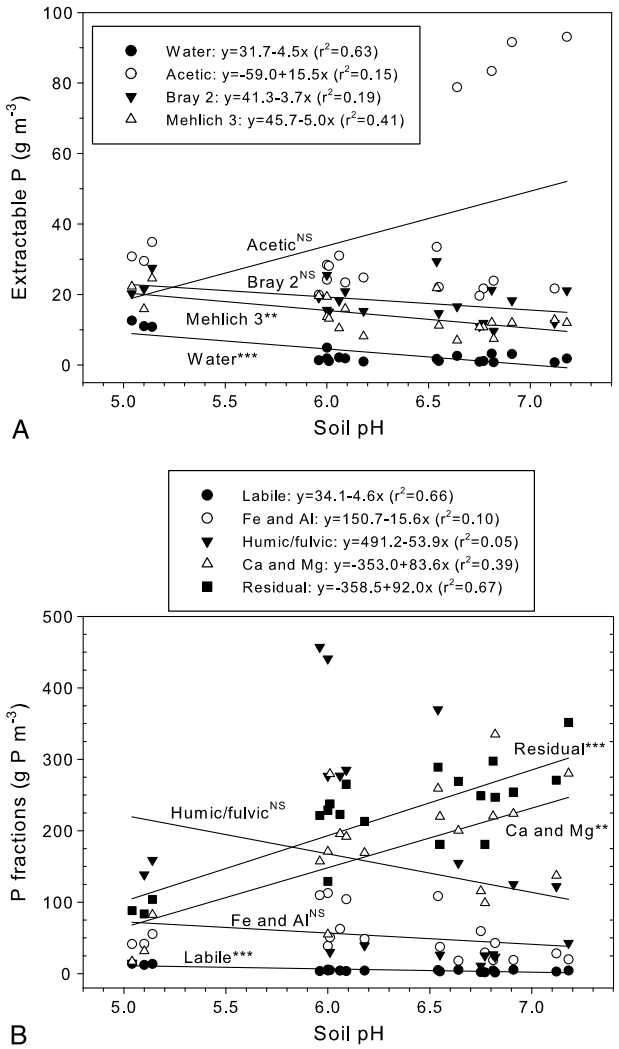

FIG. 3. Relationships between soil pH and (A) extractable soil P or (B) soil P fractions for the five Histosols in the study. Significant regressions determined at P = **0.01 and ***0.001, respectively. Nonsignificant (NS) regressions determined at P = 0.05.

humic-fulvic–bound P (r = 0.49) (Table 2, Fig. 2). Correlations of Mehlich 3 P with Ca-Mg–bound P, residual P, and total P were not significant (Table 2). The only P fractions determined to be significant in multiple regression analysis with Mehlich 3 P were labile P and Fe-Al–bound P (Table 3). Mehlich 3 P was inversely related to pH (r = −0.64) (Table 2, Fig. 3A). The P fractions extracted by Mehlich 3 are primarily labile P and Fe-Al–bound P, with some possible contribution from humic-fulvic–bound P.

Comparison of Extractants

Water-extractable P is a measure of labile P with little contribution from other P fractions. The other extractants include some measure of one or more of P fractions other than labile P. Correlations and relationships of the Bray 2 and Mehlich 3–extractable P with the various P fractions were similar (Table 2, Fig. 2), and there was a strong positive correlation between Bray 2 P and Mehlich 3 P (Table 2), suggesting that the P fractions measured by these two soil tests were generally similar for the soils studied. Regression indicated that Bray 2 included a stronger contribution from the humic-fulvic P fraction (Table 3). Also, the Bray 2 extractant included some residual P, whereas the Mehlich 3 extractant did not (Table 3). The Mehlich 3 extractant is more buffered than Bray 2 and has been reported to be less affected by free carbonate in soils (Tran et al., 1990). The Mehlich 3 extraction has also been determined to produce a less vigorous extraction of Al-bound P and Ca-bound P, which may result in a better estimate of available P compared with Bray 2 (Tran et al., 1990). The Bray 2 and Mehlich 3 procedures each have short shaking times (5 min), whereas the water and acetic acid procedures shake for 50 min each after standing overnight. The longer soil to extractant contact with the acetic acid may allow for higher dissolution of slowly available P fractions compared with a shorter extraction period (Rezaian et al., 1992).

The four P extraction methods in this study were related to sugarcane yield in a related study (McCray et al., 2012). In that study, there was a negative correlation between water P and sucrose yield. This was attributed partially to water-extractable P ranging from 8 to 12 g P m^{-3} at Site 2, which was included in both studies and where there were strong yield responses to P fertilizer. Using the water-extractable soil test, no P fertilizer would be recommended at this site (Gascho and Kidder, 1979; Rice et al., 2010). Water P was negatively correlated with pH (r = −0.79), and the elevated water P values determined at Site 2 can be attributed to the low pH (5.3) at this site (Table 1). This indicates that in acid soils the water extraction may overestimate plant-available P as determined by sugarcane yield response to P fertilizer. Because sugarcane is a long-term crop with an annual growing period of 8 to 16 months and a grand growth period of 4.5 months in Florida (Coale et al., 1993), P forms other than labile P may need to be included in a soil test. Water P essentially consists only of labile P (Tables 2 and 3), with no measure of other forms of P that may become available during a crop, and so water appears to be a poor choice as soil-test P extractant for sugarcane.

The relationship of acetic P with sugarcane yield has also been determined to be poor (McCray et al., 2012). Site 4 was included in McCray et al. (2012), and at that location, there was a strong yield response to P fertilizer even with an acetic P value of 86.7 g P m^{-3} (Table 1), which is higher than the 0 to 39 g P m^{-3} range proposed by Korndorfer et al. (1995), in which yield response would be probable. The soil at Site 4 had lower total Fe and Al compared with the other sites (Table 1), which was certainly a factor determining extractable P concentrations at that location. The acetic acid test could potentially be useful for the other four sites considered here, but a test is needed that can be used effectively for all EAA Histosols. The relationship between Bray 2 P and sugarcane yield was also determined to be poor by McCray et al. (2012). The acetic acid and Bray 2 methods do not appear to be the best choices for soil P extraction in EAA Histosols. A primary reason for this is the inclusion by each extractant of some of the more recalcitrant soil P, particularly residual P, which is not plant available (Tables 2 and 3).

McCray et al. (2012) determined a strong relationship between Mehlich 3 P and sugarcane yield and used nonlinear regression to propose a new soil-test calibration for sugarcane on EAA Histosols based on the Mehlich 3 extraction. The correlations and regressions between Mehlich 3 P and the various soil P fractions (Tables 2 and 3) can be used to explain the strong relationship between Mehlich 3 P and yield. Mehlich 3 P was determined to primarily extract labile P and Fe-Al–bound P with possible inclusion of some humic-fulvic–bound P (Tables 2 and 3). Only the more available forms of P were included in the Mehlich 3 extraction, and the more recalcitrant forms of P were excluded.

CONCLUSIONS

The percentages of the five P fractions generally increased with increasing recalcitrance in the order of labile P, Fe-Al–bound P, humic-fulvic–bound P, Ca-Mg–bound P, and residual P, with the exceptions of Sites 2 and 5 at which the highest percentage of total P was in the humic-fulvic fraction. The water extractant measured only labile P with a large increase in extractable P at less than pH 6. Acetic acid–extractable P included primarily labile P, humic-fulvic–bound P, and some residual P, one of the more recalcitrant forms of soil P. Bray 2–extractable P included labile P, humic-fulvic–bound P, and some residual P, with possible contribution from Fe-Al–bound P. There was no evidence that any of the extractants removed a significant amount of the Ca-Mg–bound fraction. Mehlich 3 was the only extractant tested that included labile and nonlabile (primarily Fe-Al bound) P while excluding the more recalcitrant residual P. Results indicate that Mehlich 3 should be the best determinant of the plant-available P pool.

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