USE OF MUCK SEDIMENTS TO IMMOBILIZE PHOSPHORUS IN FLORIDA SANDY SOILS[1]

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Phosphorus that accumulates in the surface of sandy soils is suscepti-
ble to leaching and surface runoff. Converting dissolved P to less soluble
forms using materials containing Fe, Al, and Ca can reduce the amount
of soil P released to runoff. The dredged muck of the St. Lucie Estuary
has been proposed as a manufactured soil for application on local sandy
soil. It is assumed that the application of the muck will enhance soil P re-
tention. In this study, the effects of muck sediments on water-soluble P,
Olsen-P, and P fractions of some Florida sandy soils were investigated.
In the muck type and rate experiment, two soils (a high P soil and a low
P soil) were incubated for 30 days with the mucks at 0, 5, 15, and 30%.
Application of muck reduced water-soluble P and Olsen-P significantly
in the high P soil, and also reduced water-soluble P and Olsen-P slightly
but consistently in the low P soil. When a high rate of muck (30%) was
applied, the high Fe and Al muck reduced water-soluble P by 69 to 89%
and Olsen-P by 27 to 62%, whereas the low Fe and Al muck reduced
water-soluble P by 23 to 61% and Olsen-P by 22 to 34%. At low rates
(15%), water-soluble P was reduced by 35 to 79% for the high Fe and Al
muck and 2 to 43% for the low Fe and Al muck, whereas Olsen-P was
reduced by 24 to 44% for the high Fe and Al muck and 12 to 31% for the
low Fe and Al muck. The decreased P solubility resulted from the con-
version of readily soluble P (H_2O-P and $NaHCO_3$-P) to less soluble pools
(HCl-P and residual P). Amending the high P soils with mucks has the
potential to reduce P enrichment of runoff by decreasing the solubility
of soil P. These data indicate that application of muck can result in sig-
nificant reductions in nonpoint-source P runoff from high P soils. (Soil
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soil, oxides.

PHOSPHORUS that accumulates in surface soil is susceptible to surface runoff and erosion. Some low clay soils high in soluble P are vulner-able to leaching losses of P resulting from long-term fertilizer and manure applications (Daniel et al., 1998; Sims et al., 1998). Accumulation of P in the surface soil can enhance P leaching into subsurface water or groundwater (Heckrath et al., 1995; Sharpley, 1995; Pote et al., 1996). In coarse-textured soils, the leaching losses of P are often attributed to low P adsorption because of low contents of reactive Fe and Al oxide in the soils (Khiari et al., 2000). Soil P desorption in-creases with increasing degree of P sorption sat-uration (Pautler and Sims, 2000). Many soils in the commercial citrus and vegetable crop pro-duction areas of Florida are coarse textured, low in the clay and sesquioxides that are important in immobilizing P. Repeated application of fertil-izer on these soils has increased the potential for P loss through surface runoff and leaching to groundwater (Stanley et al., 1995). The sandy

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soils with excessive P application have insufficient Al, Fe, and Ca needed to retain all of the P, and, thus, water-soluble P levels increase. Iron and Al oxides are the major solid phase components responsible for P sorption (Reddy et al., 1998). Therefore, application of materials containing large amounts of Fe and Al oxides is expected to increase P sorption and reduce P mobility. In order to reduce P in runoff from high P soil, either P loads have to be reduced or the P adsorption capacity of the soil must be raised. An effective, economical way to increase P adsorption capacity is to apply high surface area Al-, Fe-, and Ca-rich solid phase materials. Several studies have demonstrated that soluble P is readily adsorbed and/or precipitated in soils that contain Al, Fe, and Ca (Hsu, 1975; Freese et al., 1992). Aluminum, Fe, or Ca-rich materials can effectively decrease the solubility of P in soils (Soon and Bates, 1992; Corey, 1992; Lucas et al., 1994; Moore and Miller, 1994; Shreve et al., 1995; Peters and Basta, 1996; Moore et al., 1999; Codling et al., 2000; Haustein et al., 2000; Maguire et al., 2000, 2001). Chemical characterization of muck sediments reveals that they are suitable for soil amendment when applied in proper amounts (Zhang et al., 2002). It was hypothesized that muck sediment that contained large amounts of Al, Fe, Ca, clay, and organic matter could enhance P retention and might be useful as a soil amendment for reducing P runoff from soils high in available P. However, no information has been reported on reduced soluble P in soils using muck sediments.

The objective of this study was to lower soluble P in sandy soils via enchanced chemical processes (precipitation with metals and/or adsorption onto metal oxides or hydroxides) using muck sediments. The specific objectives included: (i) characterization of the P chemistry of the St. Lucie Estuary muck sediments; and (ii) examination, using a laboratory incubation study, of the effects of muck application on reduction of water-soluble P in Florida sandy soils.

MATERIALS AND METHODS

Muck Sediments

Muck samples (59) were collected by the Army Corps of Engineers from the St. Lucie Estuary and delivered to the University of Florida, Indian River Research and Education Center. The samples were stored in a freezer after their arrival. Prior to chemical analysis, each sample was transferred from the sampling tube to a polyethylene bag, mixed thor-

oughly in a plastic bag, air-dried, and ground to pass a 2-mm mesh sieve. The sediment samples were used for measuring pH and electrical conductivity (EC) and for incubation experiments. Subsamples of the air-dried muck were ground further to pass a 0.15-mm mesh sieve and analyzed for total organic carbon (C), nitrogen (N), phosphorus (P), magnesium (Mg), calcium (Ca), manganese (Mn), aluminium (Al), and iron (Fe).

Soils

The 24 soil samples (24) used in this study were collected from 24 commercial vegetable farms and citrus groves in the Indian River area, Florida. Soil classes for the 24 soil samples were Wabasso sand (sandy, siliceous, hyperthermic alfic haplaquods) and Nettles sand (sandy, siliceous, hyperthermic, ortstein alfic arenic haplaquods). The soils were collected at 0 to 15 cm (Ap horizon). After sampling, the soils were air-dried and ground to pass through a 2-mm sieve. Subsamples of the air-dried soils were further ground to pass a 0.15-mm mesh sieve for measurement of total P, Fe, Al, Mn, Ca and Mg. These soils had similar textures and organic matter contents but different soil test P values. They contained more than 900 g kg^{-1} of sand, less than 60 g kg^{-1} of silt and clay, 10 to 27g kg^{-1} of organic C, and 11.4 to 141 mg kg^{-1} of Olsen P.

Incubation Study

Two soils (a high available P soil (HP) and a low available P soil (LP)) and two typical muck sediments (a high Fe, Al muck (HFe) and a low Fe, Al muck (LFe)) were selected for this experiment (see Table 1). Since increasing the transport distance increases the cost of muck disposal, it was proposed that the dredged muck sediment be manufactured as soil products, combining muck blended with cellulose material and biosolids for use as topsoil and using a mixture of 50% muck plus 50% nursery potting mixture for potting soil (Sturgis et al., 1997). The rate of muck application may vary from low to high levels, depending on the salt content in the muck (Sturgis et al., 1997). Therefore, a wide range of muck application rates was selected for this study. Four rates of the two muck sediments (0, 5, 15, and 30%) were thoroughly mixed with 2.0 kg duplicate soil samples. After mixing, the mixture was wetted to 20% moisture content (oven-dry basis), placed in a plastic box (35 cm × 20 cm × 20 cm) with a small opening, and incubated at 25 °C for 30 days. The moisture content was maintained at 20% during the incubation period.

TABLE 1
Selected properties of the sediments and soils

Samples†	pH (H₂O)	EC (dS m⁻¹)	Organic C (g kg⁻¹)	Water-soluble P (mg kg⁻¹)	Olsen-P (mg kg⁻¹)	Total (g kg⁻¹)					Particle size (g kg⁻¹)		
						P	Fe	Al	Ca	Mg	Sand	Silt	Clay
HFe (muck)	6.18	2.22	53.7	0.85	23.4	1.51	26.0	43.8	7.82	3.32	198	422	380
LFe (muck)	7.57	2.05	41.0	1.32	25.6	0.82	13.0	14.4	33.6	2.66	602	191	207
HP (soil)	7.43	0.30	5.36	8.60	60.8	0.38	0.69	1.03	1.06	0.16	947	27	26
LP (soil)	5.52	0.14	3.67	1.20	11.4	0.05	0.54	0.74	0.30	0.09	960	7	33

†HFe: High Fe and Al muck sample; LFe: Low Fe and Al muck sample; HP: High available P soil sample; LP: Low available P soil sample.

At the end of the incubation period, subsamples of the muck-amended soils were used for extraction of soil solution and sequential leaching. Soil solutions were extracted by centrifugation. A polycarbonate centrifuge bottle was modified by cutting off its top and base. A filtering plate was constructed from a porous polycarbonate material to fit between the base and the body of the centrifuge bottle. A Whatman #1 filter paper was placed on the filtering plate, and 50-g moist soil was loaded into the bottle. The base of the bottle was then taped in place below the filtering plate, and the moist soil was centrifuged at 2000 × g (rcf) for 15 min. After centrifugation, the base of the bottle was removed and the supernatant was again filtered through a Whatman #42 filter paper. Soil solution samples (four replicates) were obtained from each treatment for each sampling event. Concentrations of P in the soil solution were measured using an inductively coupled plasma atomic emission spectroscopy (ICP-AES, Ultima, J-Y Emission Division Instruments SA, Inc., Edison, NJ).

In the leaching experiment, the muck-amended or unamended soil samples (50 g) were placed onto a Whatman #42 filter paper in a funnel and leached with 50 mL of distilled water. The leaching was repeated daily for a total of six sequential leachings. Leachates were collected in a 125-mL polyethylene bottle. After each leaching, the leachate was filtered and analyzed for P using the ICP-AES.

Eight soils with different levels of available P were selected to examine the effects of muck amendments on water-soluble P and Olsen-P in the soils. Duplicate soil samples (150 g each treatment) were mixed thoroughly with muck sediments at two rates (15% and 30%) in a series of 250-mL polyethylene bottles. The soil preparation and incubation procedures were the same as described above. At the end of the 30-d incubation, the muck-amended soils were analyzed for water-soluble P and Olsen-P.

Measurements of Basic Properties and Total P, Fe, Al, Mn, Ca and Mg Contents

Soil (or muck) pH was measured in water at a soil (muck): water ratio of 1:1, and EC was measured in water at a soil (muck): water ratio of 1:2 using a pH/ion/conductivity meter (Accumet Model 50, Fisher Scientific) (Thomas, 1996). Total organic C was determined using a CNS-Analyzer (NA 1500, Fisons Instruments Inc., Dearborn, MI). Particle size of the soil (muck) samples was determined using a micropipette method (Miller and Miller, 1987).

Muck or soil sample (0.5 g) was digested in a mixture solution of 9 mL HNO_3 and 3 mL HF using a Microwave Digestion System (O· I·Analytical, College Station, TX) and following the USEPA Method 3052 (USEPA, 1995). The concentrations of P, Fe, Al, Mn, Ca, and Mg were determined using the ICP-AES.

Measurement of Soil P Availability Indexes

Subsamples of muck sediment and soil samples and muck-amended soil samples were analyzed for P availability indexes by the following extraction methods: (i) Olsen-P [1:20 ratio of soil to 0.5 mol L^{-1} $NaHCO_3$ (pH 8.5); 30-min reaction time (Kuo, 1996)]; (ii) water-soluble P [1:10 ratio of soil to deionized water; 60-min reaction time (Kuo, 1996)]; (iii) Mehlich 3-P [1:10 ratio of soil to solution; 5-min reaction time (Mehlich, 1984)]. After each extraction, the suspension was centrifuged at 2500 × g (rcf) for 30 min to obtain a clear supernatant, the supernatant was filtered through a Whatman #42 filter paper. Phosphorus concentrations in the extracts of water and $NaHCO_3$ were determined colorimetrically by the molybdenum blue method (Olsen and Sommers, 1982). Phosphorus, Fe, and Al concentrations in the extracts of Mehlich 3 were determined using the ICP-AES. The acid ammonium oxalate extraction was performed according to Mckeague and Day (1966), P (Pox), Fe (Feox), and Al (Alox) was quantified by the ICP-AES. Molar percentage of [P/(Fe+Al)] was calculated from P, Fe, and Al concentrations extracted by the Mehlich 3 and acid ammonium oxalate.

Phosphate Sorption

The 59 muck sediments and 24 surface soil samples were used for measuring P sorption capacity. Phosphorus sorption isotherms were determined as follows: portions of soil sample, each containing 1.00 g, were placed in polystyrene centrifuge tubes, and 30 mL of 0.02 M KCl solution containing 0, 2.5, 5.0, 7.5, 10.0, 15.0, or 20 mg P L^{-1} was added to each tube. The tubes were shaken on an end-on-end shaker for 24 h at 25 °C. At the end of the designated time, the suspensions were centrifuged at 3000 × g (rcf) for 10 min and filtered through Whatman #42 filter paper. Phosphorus concentrations in the filtered solution were determined colorimetrically using the molybdenum blue method (Olsen and Sommers, 1982). The simple Langmuir equation was employed to describe P sorption. The adsorption maximum (Q_m) was obtained from the Langmuir equation, which is expressed as:

$$Q = KC Q_m/(1 + KC), \qquad (1)$$

where Q is the amount of P adsorbed (mg P kg^{-1} soil), C is P concentration in the equilibrium solution (mg P L^{-1}), Q_m is the adsorption maximum, and K is a constant related to P binding energy.

Fractionation of Soil Phosphorus

Muck sediment samples (59) and the muck-amended soil samples were used for measuring soil P fractionation. A modified method of Hedley et al. (1982) was selected in this study to determine soil P fractions. Soil samples (each containing 1.0 g) were placed in 50-mL centrifuge tubes and extracted sequentially with 30 mL of deionized water, 0.5 mol L^{-1} $NaHCO_3$ (pH = 8.2), 0.1 mol L^{-1} NaOH, and 1 mol L^{-1} HCl. Each extraction lasted for 16 h on an end-to-end shaker (180 cycles/min). After each extraction, the tubes were centrifuged at 2500 × g (rcf) for 30 min, and the supernatant was then passed through a Whatman #42 filter paper. The P concentrations in the filtrates from deionized water, HCl, $NaHCO_3$, and NaOH extracts were determined colorimetrically by the molybdenum-blue method after digestion with acidified ammonium persulfate (Greenberg, 1992). Residual-P was calculated by subtracting the sum of above four extractable P frctions from the total P content in the sample. Based on sequence of the extractions, soil P fractions were referred to as water-soluble P (H_2O-P), plant-bioavailable P ($NaHCO_3$-P), potentially plant-bioavailable P (NaOH-P), acid soluble P (Ca-bound P/HCl-P), and residual P.

RESULTS AND DISCUSSION

Characteristics of the Muck Sediments

Contents of Iron, Aluminium, Manganese, Calcium, Magnesium, and Phosphate Adsorption Capacity

Iron, Al, Mn, Ca, and Mg contents varied among the muck samples. The concentration ranges of the elements were 1.57–37.0 g kg^{-1} for Fe, 4.22–59.9 g kg^{-1} for Al, 0.023–0.22 g kg^{-1} for Mn, 0.96–40.4 g kg^{-1} for Ca, and 0.15–16.6 g kg^{-1} for Mg. The mean Fe, Al, Mn, Ca, and Mg contents in the mucks were 17.3, 29.6, 0.12, 18.6, and 2.87 g kg^{-1}, respectively, which were 17.1, 8.1, 3.2, 7.5, and 14.1 times higher than those in the sandy soils. Higher Al, Fe, and Ca contents in the mucks indicate that the mucks have great potential for decreasing P solubility in the sandy soils by chemical fixation.

Maximum P sorption (Q_m) of the mucks, ob-

tained from the Langmuir equation, varied from 39.5 to 1046.2 mg kg^{-1}, with a mean of 457.1 mg kg^{-1}. Phosphate adsorption capacity for the mucks was much higher than for the sandy soils (23.51–61.92 mg kg^{-1}), and the mean of Q_m values in the mucks was about 12 times greater than that in the sandy soils. Contents of Al, Fe, and organic matter were the major contributions to P sorption capacities in the mucks. The Q_m was significantly and positively correlated with Al, Fe, organic matter, and oxalate-extractable Fe (Feox) and Al (Alox) contents (Table 2). The Q_m values were more strongly correlated with Fe ($r = 0.68$) than with other components, suggesting that Fe content had the greatest effect on muck P sorption capacity. The high P adsorption capacity (Q_m) suggests that the mucks may have more potential in reducing P loss through surface runoff and subsurface leaching when amended to the sandy soils.

Total Phosphorus and Availability Indexes of Phosphorus

Total P content in the mucks ranged from 0.34 to 1.99 g kg^{-1}, averaging 1.11 g kg^{-1}. Water-soluble P in the mucks ranged from 0.70 to 9.51 g kg^{-1}, and 75% of the muck samples had a water-soluble P between 1 and 3 g kg^{-1}. The percentage of total P that was water-soluble was generally low, however, ranging from 0.10 to 0.63%. Forty-six of the 59 muck samples had water-

TABLE 2

Correlation coefficients (r) between P maximum adsorption (Qm), total P, water-soluble P, Mehlich 3 extractable P and properties of muck sediments (n=59)

Fractions	Q_m	Total P	Water-soluble P	Mehlich 3-P
Total Al	0.40**	0.65**	0.11	0.27*
Total Ca	−0.20	0.42**	0.39**	0.39**
Total Fe	0.68**	0.76**	0.20	0.28*
Total Mg	−0.05	0.571**	0.25	0.41**
Total Mn	0.25	0.80**	0.43**	0.52**
Organic matter	0.27*	0.83**	0.61**	0.76**
Feox†	0.32*	0.42**	0.07	0.08
Alox†	0.34**	0.86**	0.50**	0.63**
PH	−0.84**	−0.26*	−0.02	0.04
EC	0.55**	0.61**	0.31*	0.32*
Sand	−0.13	−0.78**	−0.71**	−0.57**
Silt	0.34**	0.82**	0.65**	0.54**
Clay	−0.07	0.68**	0.70**	0.55**

*,**: Significant at $p < 0.05$ and < 0.01 level, respectively.
†Feox: Oxalate-extractable Fe; Alox: Oxalate-extractable Al.

soluble P content less than 0.2% of the total P. Mehlich 3 extractable P in the mucks was relatively high, ranging from 11.6 to 103 mg kg^{-1} and averaging 34.65 mg kg^{-1}. However, the percentage of the Mehlich 3 extractable P in the total P was low, generally from 2 to 4%. These data suggest that the proportion of available P in the muck total P is low and there is also low P release potential. Water-soluble P was correlated positively with total Ca and Mn contents and with organic matter, EC, silt, and clay contents and was negatively correlated with sand content (Table 2). The Mehlich 3-P was correlated positively with total Al, Ca, Fe, Mg, Mn concentrations, organic matter, EC, and silt and clay contents and negatively correlated with sand content (Table 2).

The [P/(Fe+Al)] ratios calculated from P, Fe, and Al concentrations extracted by Mehlich 3 or oxalate were used to predict P loss potential by runoff and leaching under field conditions (Khiari et al., 2000; Pautler and Sims, 2000). Most muck samples had Pox/(Fe + Al)ox below 0.15 and P_{M3}/(Fe + Al)$_{M3}$ less than 0.25. The low ratios suggest that the mucks have low P saturation and availability. Water-soluble P in the mucks increased with the Pox/(Fe + Al)ox and P_{M3}/(Fe + Al)$_{M3}$ (Fig. 1).

Phosphorus Fractionation

The concentrations of P fractions and their percentages in the total P are summarized in Table 3. Sequential extraction of the muck samples with deionized water, $NaHCO_3$, NaOH, and HCl indicated that, on average, about half of the P in the mucks was extractable to water, mild alkaline, or acid medium. However, the concentrations of all P fractions or their percentages in the total P varied greatly among the 59 muck samples (Table 3). Mean percentages of each P fraction in the total decreased in the order of residual-P (50.4%) > NaOH-P (33.5%) > HCl-P (11.6%) > $NaHCO_3$-P (4.1%) > H_2O-P (0.4%). The percentage of H_2O-P in the total P was the lowest among all the fractions. The percentages of H_2O-P, $NaHCO_3$-P, NaOH-P, HCl-P, and residual-P in the total P were generally <0.4, 3.1–5.0, 20–60, <20, and 40–60%, respectively for most of the samples (Fig. 2). Compared with sandy soils (Table 3), the mucks had less H_2O-P and $NaHCO_3$-P, and more NaOH-P and residual-P. The H_2O-P was correlated positively with total Ca, Mn, P concentrations, organic matter, and silt, and clay contents and negatively correlated with sand content. The $NaHCO_3$-P was correlated positively with total Al, Ca, Mg, Mn, P con-

$$Y = 0.60 \exp (0.10X)$$
$$(R^2 = 0.57, p<0.0001)$$

$$Y = 1.12 \exp (0.040X)$$
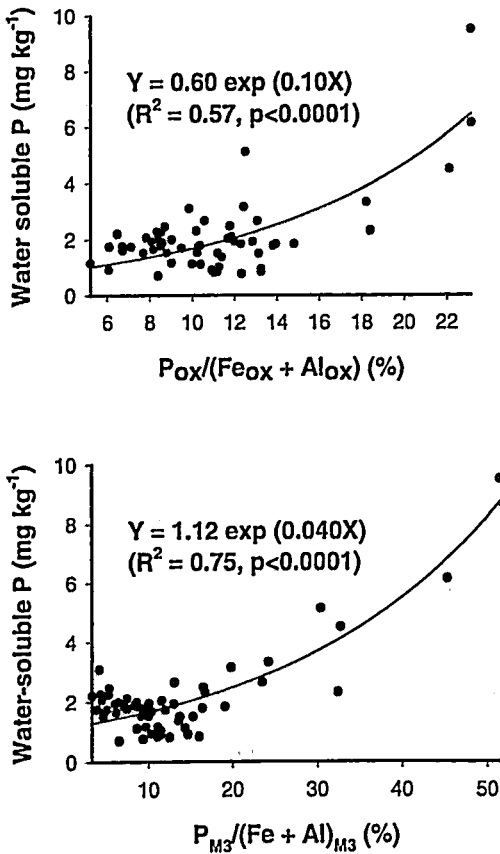$$(R^2 = 0.75, p<0.0001)$$

Fig. 1. Relationship between P saturation indexes and water-soluble P in 59 muck sediments. $P_{ox}/(Fe + Al)_{ox}$ and $P_{M3}/(Fe + Al)_{M3}$ were ratios of P to (Fe + Al) in oxalate and Mehlich 3 extracts, respectively.

centrations, organic matter content, EC, and silt and clay contents and negatively correlated with sand content. The NaOH-P was correlated with each variable except for pH. The HCl-P was cor-

related with each variable except for total Al and pH. Residual-P was correlated positively with total Al, Fe, Mg, Mn, P concentrations, organic matter content, EC, and silt content but negatively correlated with pH (Table 4).

Muck Effects on Soil Phosphorus

Soil Water-Soluble Phosphorus and Olsen-P

Application of mucks decreased water-soluble P and Olsen-P in the soils. The high Fe and Al mucks were more effective in reducing available P than were the low Fe and Al mucks. For soil high in available P, water-soluble P and Olsen-P were significantly decreased by muck amendment. Water-soluble P, and Olsen-P decreased with increasing rate of the mucks (Fig. 3). In contrast, for soil low in available P, water-soluble P and Olsen-P were minimally affected by muck application (Fig. 3). The effect of muck was greater on water-soluble P than on Olsen-P. At the highest muck rates (30%), the high Fe and Al mucks reduced water-soluble P by 78% and Olsen-P by 62% in the high available P soils, whereas low Fe and Al mucks reduced water-soluble P and Olsen-P by 62% and 34%, respectively.

Compared with calculated weight-averaged values of P in the sediment-amended soils, based on proportions of the mucks and water-soluble P and Olsen-P concentrations in the mucks and soils, the measured water-soluble P and Olsen P concentrations in the sediment-amended soils were much lower. For the high Fe and Al muck-amended soils at the low muck rate (5%), water-soluble P concentration was 45% lower than the calculated values in the high available P soil, whereas Olsen P concentration was 21% lower. For the high Fe and Al muck-amended soils at the

TABLE 3

Summary of P fractionation of the 59 muck sediments

| Samples	Depth (cm)	Total-P	H_2O-P	$NaHCO_3$-P	NaOH-P	HCl-P	Residual-P
				Concentration (P, mg kg^{-1})			
	Range	345–1992	1.6–21.0	21.6–109	31.5–889	1.0–440	158–878
Muck	Mean	1106	4.4	43.5	400	133	524
Sediments				Proportion in the total P (%)			
(n = 59)	Range	100	0.2–1.4	1.8–8.3	6.3–60.8	0.2–26.4	18.0–87.4
	Mean	100	0.4	4.1	33.5	11.6	50.4
				Concentration (P, mg kg^{-1})			
	Range	85.9–552	6.6–45.5	21.3–150	9.6–58.1	5.1–162	3.5–338
Soil	Mean	266	23.8	73.0	32.9	69.1	67.3
(n = 24)				Proportion in the total P (%)			
	Range	100	2.5–15.5	6.2–45.6	3.7–19.5	5.1–51.0	1.2–61.3
	Mean	100	9.4	28.2	13.4	23.6	25.4
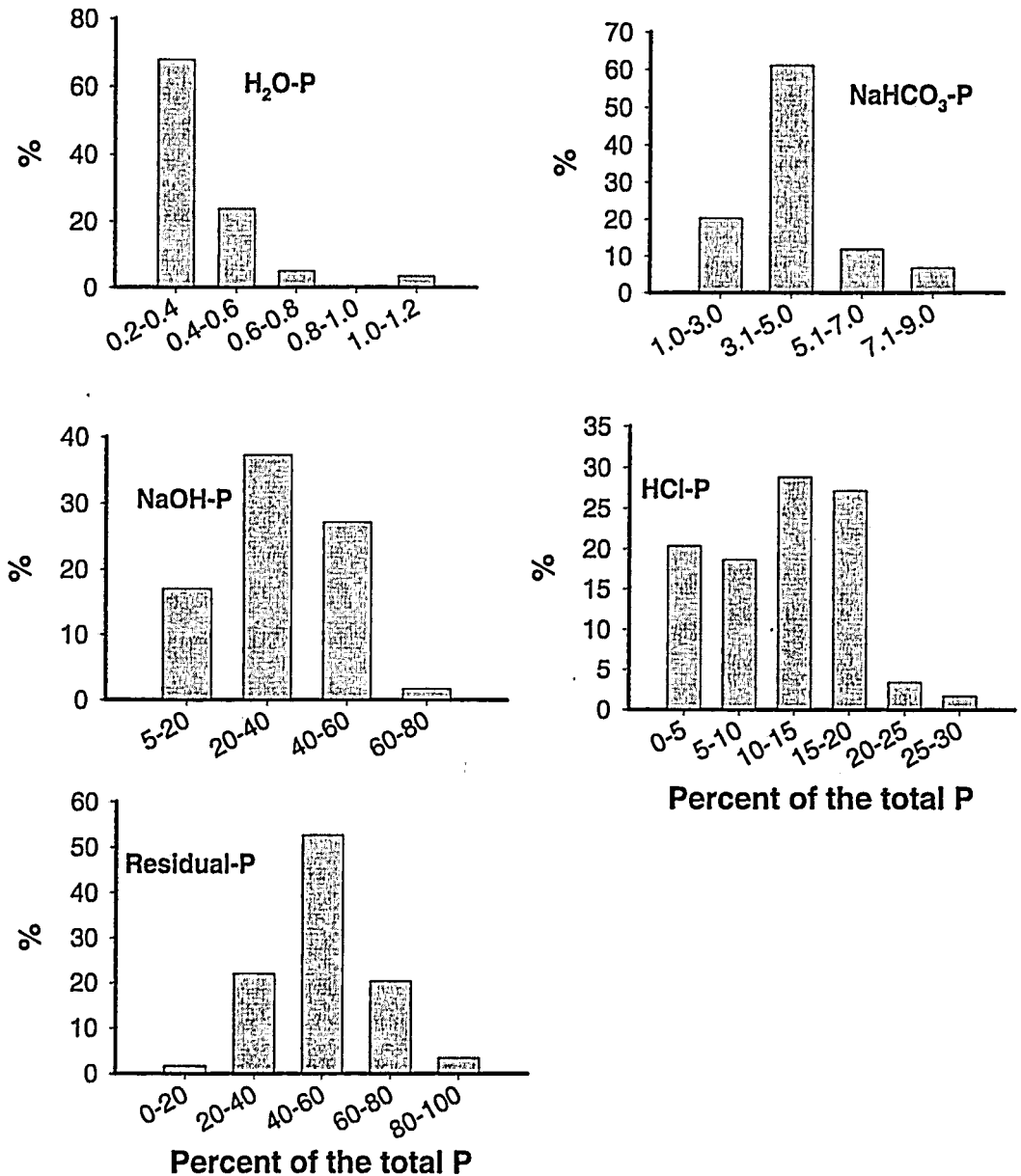
Fig. 2. Frequency distribution of the five P fractions in the 59 muck samples.

high muck rate (30%), water-soluble P concentration was 70% lower than the calculated values in the high available P soil, whereas Olsen P concentration was 53% lower. For low Fe and Al muck-amended soils at the muck rates of 5 and 30%, measured water-soluble P concentrations in the high available P soil were 38 and 48%, lower, respectively, than the calculated values, whereas those in the low available P soil were 17 and 60%, lower, respectively, than the calculated values. The

results suggest that water-soluble P and Olsen P reduction in the muck-amended soils is caused by chemical fixation of P by the mucks rather than by P dilution caused by muck addition.

After application of the mucks, the reduced proportion of water-soluble P in the muck-amended soil increased with increasing soil water-soluble P level, muck rate, and Fe and Al content in the mucks. When a high rate of muck (30%) was applied, application of low Fe and Al mucks

TABLE 4

Correlation coefficients (r) between P fractions and properties of muck sediments (n=59)

Fractions	H$_2$O-P	NaHCO$_3$-P	NaOH-P	HCl-P	Residue-P
Total Al	0.08	0.37**	0.39**	0.12	0.89**
Total Ca	0.38**	0.33**	0.48**	0.74**	−0.11
Total Fe	0.16	0.24	0.80**	0.41**	0.46**
Total Mg	0.23	0.48**	0.38**	0.46**	0.52**
Total Mn	0.39**	0.45**	0.85**	0.68**	0.33*
Total P	0.53**	0.72**	0.91**	0.69**	0.67**
Organic matter	0.59**	0.72**	0.76**	0.70**	0.46**
pH	−0.01	−0.06	−0.22	0.25	−0.44**
EC	0.28*	0.37**	0.58**	0.38**	0.40**
Sand	−0.55**	−0.58**	−0.82**	−0.86**	−0.19
Silt	0.52**	0.56**	0.87**	0.78**	0.26*
Clay	0.54**	0.54**	0.70**	0.87**	0.12

*, **: Significant at p < 0.05 and < 0.01 level, respectively.

reduced soil water-soluble P by 23 to 61%, whereas soil water-soluble P was reduced by 69 to 89% as a result of application of high Fe and Al muck. At low rates (15%), water-soluble P was reduced by 35 to 79% for high Fe and Al muck, and 2 to 43% for low Fe and Al muck. The decrease in Olsen-P in the muck-amended soil also increased with muck rate and Fe and Al content in the mucks, but change in the reduced proportion of Olsen-P with soil Olsen-P level was not obvious. Application of high-Fe and Al mucks decreased soil Olsen-P by 27 to 62% at the high rate (30%), and 24 to 44% at the low rate (15%), whereas soil Olsen-P was reduced by 22 to 34% at the high rate (30%) and 12 to 31% at the low rate (15%) by application of the low Fe and Al muck.

Phosphorus Concentrations in Soil Solution and Leachates

Application of muck decreased concentrations of P in the soil solution of soils with high available P from 8 to 3 mg L^{-1} using the high Fe and Al muck and from 8 to 5 mg L^{-1} using the low Fe and Al muck. However, for low available P soils, addition of muck did not significantly change soil solution P levels. The concentrations of P in the leachates from muck-amended soils were lower than those of the controls (unamended soils) (Fig. 4). For high available P soils, application of the high Fe and Al muck decreased P in leachates from 2.8 to <1 mg L^{-1}, whereas application of the low Fe and Al muck decreased P concentration from 2.8 to 1.5 mg L^{-1}. For the
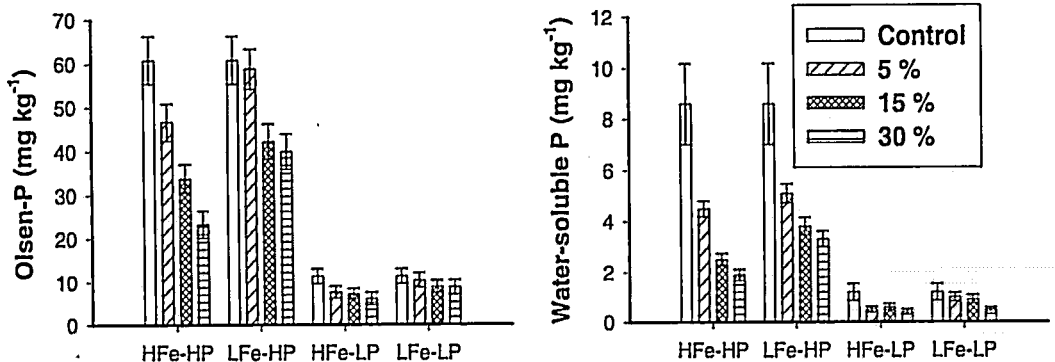

Fig. 3. Effects of muck application on water-soluble P and Olsen-P in the soils. HFe: High Fe and Al muck; LFe: Low Fe and Al muck; HP: High available P soil; LP: Low available P soil. Error bars represent standard error.
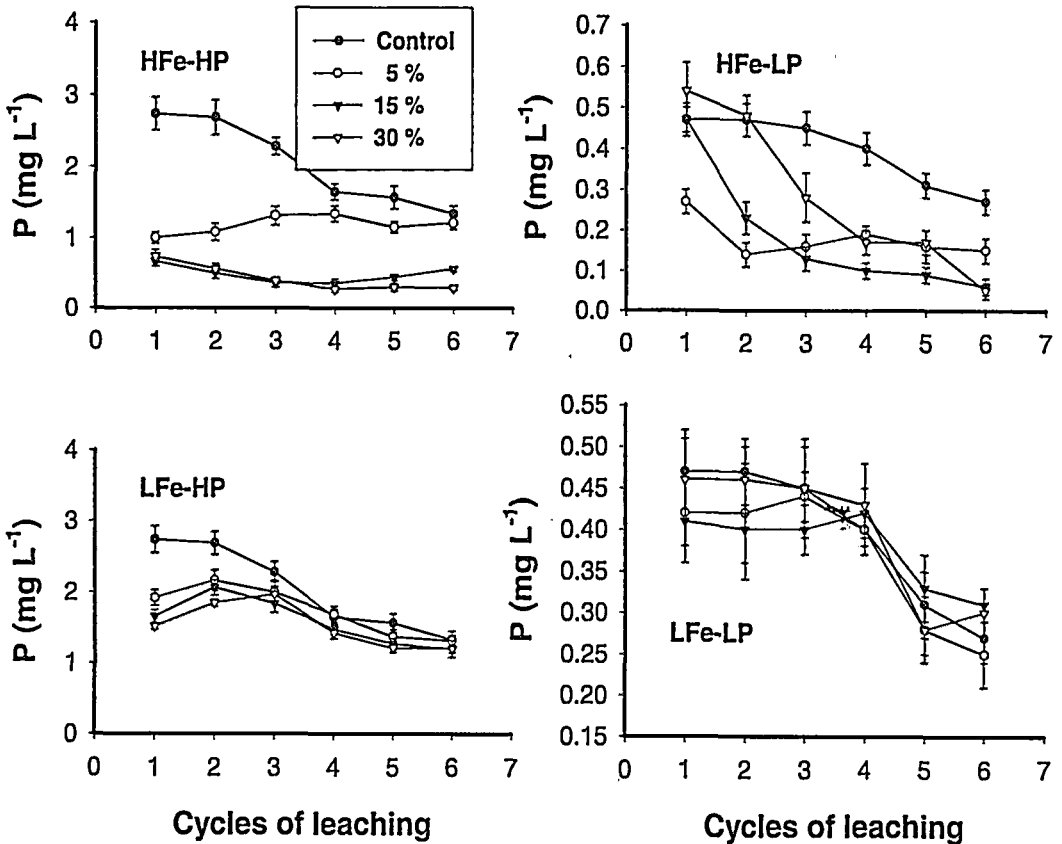
Fig. 4. Effects of muck application on P concentrations in leachates. HFe: High Fe and Al muck; LFe: Low Fe and Al muck; HP: High available P soil; LP: Low available P soil. Error bars represent standard error.

low available P soils, application of mucks decreased P level in the leachates slightly.

Soil Phosphorus Fractions

Amendment of the mucks increased total P in the muck-amended soils significantly (Table 5). The differences in total P found in the muck-amended compared with the unamended soils were most pronounced because of the higher P concentration in the muck than in the unamended soil. Total P in the muck-amended soils increased with muck rate applied. The concentrations of all P fractions were significantly influenced by muck addition. The H_2O-P decreased with increasing muck rate when the high Fe and Al mucks were applied and decreased slightly with increasing muck rate when the low Fe and Al mucks were applied. Significant decreases in $NaHCO_3$-P from muck application occurred only in the high available P soil when the high Fe and Al muck were applied. For low available P soils or when the low Fe and Al muck was

applied, the decrease in $NaHCO_3$-P was not significant. Effect of muck amendment on NaOH-P in soil varied with muck type and soil available P level. Application of the high Fe and Al mucks increased significantly the concentration of NaOH-P in both low and high available P soils. However, application of the low Fe and Al mucks increased slightly NaOH-P concentration in low available P soil, but it decreased NaOH-P concentration in high available P soils. Application of mucks increased both HCl-P and residual-P. These data indicated that application of the mucks decreased soil labile P [water-soluble P and (H_2O-P) and bioavailable P ($NaHCO_3$-P)] and increased less water-soluble P fractions, including potentially bioavailable P (NaOH-P), acid soluble P (Ca-bound P/HCl-P), and residual P.

Mechanism of Muck Immobilizing Phosphorus

Muck amendment resulted in a shift from readily available water-soluble P and $NaHCO_3$-P pools to NaOH-P, HCl-P, and residual-P in the

TABLE 5
Phosphorus fractionation of muck-amended soils

Treatments[†]	Rates of muck (%)	H_2O-P (mg kg^{-1})	NaHCO$_3$-P (mg kg^{-1})	NaOH-P (mg kg^{-1})	HCl-P (mg kg^{-1})	Residual-P (mg kg^{-1})	Total-P (mg kg^{-1})
HFe-HP	0	34.5 (3.23)[‡]	113 (7.13)	78.2 (5.43)	95.9 (5.68)	54.2 (2.74)	376 (4.47)
	5	23.9 (2.14)	107 (6.29)	101 (6.49)	117 (6.03)	72.4 (2.97)	421 (4.52)
	15	9.6 (1.67)	83.1 (4.77)	89.8 (6.03)	121 (6.66)	212 (5.37)	516 (5.12)
	30	2.8 (0.42)	58.6 (4.06)	103 (5.92)	118 (6.02)	328 (6.08)	610 (5.77)
LFe-HP	0	34.5 (3.23)	113 (7.13)	78.2 (5.43)	95.9 (5.74)	54.2 (2.74)	376 (4.47)
	5	29.7 (2.52)	98.5 (5.41)	82.2 (5.03)	132 (5.96)	41.4 (2.06)	374 (4.47)
	15	31.3 (3.27)	101 (5.47)	56.5 (4.17)	119 (5.43)	115 (4.11)	423 (5.13)
	30	24.8 (3.01)	88.5 (5.02)	43.0 (4.06)	121 (5.55)	183 (5.28)	460 (5.28)
HFe-LP	0	6.0 (1.16)	15.6 (2.97)	7.7 (1.23)	4.2 (1.07)	18.6 (2.14)	52.1 (1.36)
	5	3.1 (0.42)	15.3 (2.76)	17.3 (3.24)	9.8 (2.02)	71.2 (3.06)	117 (1.95)
	15	1.3 (0.28)	14.8 (2.41)	22.1 (3.68)	23.1 (2.69)	174 (4.53)	235 (2.04)
	30	1.0 (0.13)	13.8 (2.35)	23.4 (3.41)	36.2 (3.04)	306 (7.17)	381 (3.13)
LFe-LP	0	6.0 (1.16)	15.6 (2.97)	7.7 (1.23)	4.2 (1.07)	18.6 (2.14)	52.1 (1.36)
	5	5.8 (1.09)	14.0 (2.32)	9.5 (2.45)	10.1 (2.14)	43.3 (2.27)	82.7 (1.03)
	15	5.7 (1.14)	13.1 (2.44)	10.1 (2.44)	23.8 (2.78)	94.1 (4.08)	147 (1.28)
	30	5.1 (0.89)	14.2 (2.40)	13.5 (2.76)	48.3 (3.99)	140 (4.67)	222 (2.07)

[†]HFe: High Fe and Al muck sample; LFe: Low Fe and Al muck sample; HP: High available P soil sample; LP: Low available P soil sample.
[‡]Mean (standard deviation).

soils. This shift is consistent with increased Fe and Al contents as a result of the muck addition. The highest application rate actually decreased H_2O-P by 83 to 92% for the high Fe and Al mucks and by 15 to 28% for the low Fe and Al mucks, while decreasing NaHCO$_3$-P by 12 to 48% for the high Fe and Al mucks and 9 to 22% for the low Fe and Al mucks (Table 5).

Application of muck had only a small effect on soil pH, but it had a great effect on soil oxalate-extractable Fe and Al, and oxalate-extractable Fe and Al concentrations generally increased with muck rate (Fig. 5). The increase in oxalate-extractable Fe and Al coincided with a sharp decline in the amount of water-soluble P. The decrease in water-soluble P was roughly proportional to the amounts of added Fe and Al contents (Fig. 6). Obviously, changes in oxalate-extractable Fe and Al concentrations of the soils explain, in part, the changes in P adsorption. Variations in the percentage of oxalate-extractable P to Fe and Al [Pox/(Feox + Al ox] explained about 91% of the variation in water-soluble P for all soils (Fig. 6). The decline in available P apparently resulted from the increased Fe and Al contents in the soils (Fig. 5). The mechanisms of water-soluble P decrease in the muck-amended soils are related to enhanced interactions (precipitation and adsorption) of P with increased Fe and Al oxides from muck application.
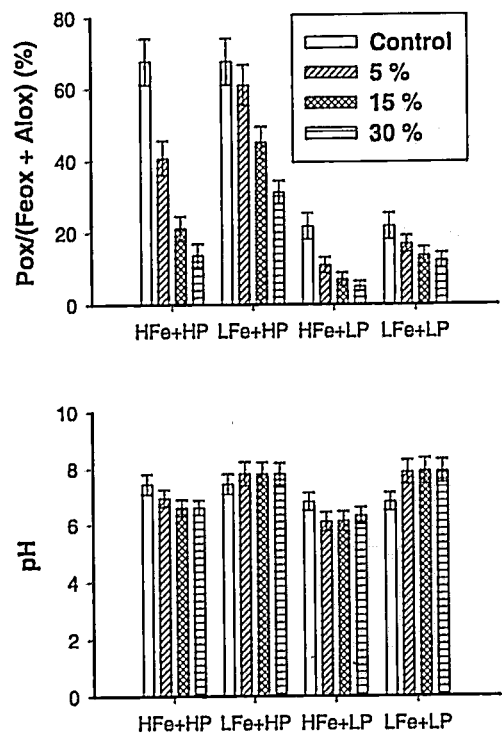

Fig. 5. Effects of muck application on soil pH and percentage of Pox to (Fe + Al)ox. HFe: High Fe and Al muck; LFe: Low Fe and Al muck; HP: High available P soil; LP: Low available P soil. Error bars represent standard error.
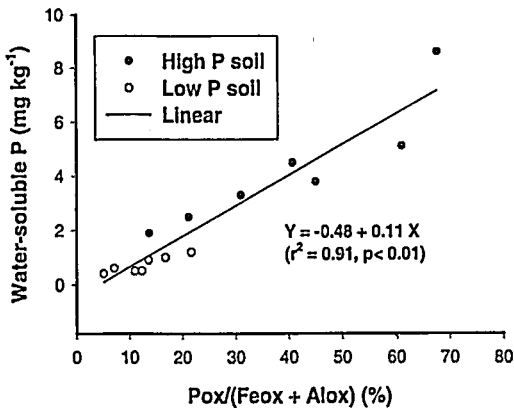
Fig. 6. Relationship between water-soluble P and Pox/(Fe + Al)ox of the muck-amended soils.

CONCLUSIONS

It has been proposed that dredged muck sediments be used in the manufacture of soil products, with possible uses as topsoil or potting soil additives. The rate of muck application to the soil may vary from low to high. Proper application rates have the potential to reduce P enrichment in runoff, which is important to minimizing P export. The reduced proportion of water-soluble P and Olsen-P in the muck-amended soil increased with increasing rate of muck applied and the content of Fe and Al in the mucks. The decrease in water-soluble P in the muck-added soils resulted from the conversion of water-soluble P to less soluble Fe- and Al-bound P fractions. The muck application affected Olsen-P less than water-soluble P. These data indicate that application of mucks at 15 to 30% can effectively decrease nonpoint source P runoff from high P soils. From an agronomic perspective, the use of mucks will be beneficial in high P soils where P loss in runoff is a concern.

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