RELEASE POTENTIAL OF PHOSPHORUS IN FLORIDA SANDY SOILS IN RELATION TO PHOSPHORUS FRACTIONS AND ADSORPTION CAPACITY

M. K. Zhang,[1] Z. L. He,[1,2,*] D. V. Calvert,[2] P. J. Stoffella,[2] Y. C. Li,[3] and E. M. Lamb[2]

[1]College of Resource and Environmental Sciences,
Zhejiang University, Huajiachi Campus,
Hangzhou 310029, P. R. China
[2]University of Florida, Institute of Food and Agricultural Sciences,
Indian River Research and Education Center, 2199 South Rock
Road, Fort Pierce, FL 34945, USA
[3]University of Florida, Institute of Food and Agricultural Sciences,
Tropical Research and Education Center,
Homestead, FL 33031, USA

ABSTRACT

Information on P release potential in relation to labile P and P fractions in sandy soils is limited. In this study, P release potential was determined by leaching, and labile P, soil P fractionation, and P adsorption capacity were measured in the laboratory using 96 Florida sandy soil samples to evaluate the relationship between P release in water and soil P status. The sandy soils had a very low P adsorption capacity. The adsorption maximum, as calculated from the Langmuir equation, averaged 40.4 mg P kg^{-1}. More than 10% of the soil P was water soluble, indicating a high risk of P leaching from soil to water. Successive leaching using deionized water released, on average, 7.7% of total P (144.5 mg kg^{-1}) in different soils, whereas labile P recovered by successive

*Corresponding author. E-mail: zhe@mail.ifas.ufl.edu

water extraction accounted for 39.2% of the total P. Variation in P release potential among the different soils could be explained more by the difference in amounts of extractable P than the adsorption capacity. Total amounts of P released by successive leaching were significantly correlated with all labile P indices measured by different methods and all soil P fractions except for residual P. The correlation coefficients (r) were 0.97** for water-soluble P, 0.96** for 0.01 M $CaCl_2$-P, 0.94** for Olsen P, 0.86** for Mehlich 1-P, 0.77*** for Mehlich 3-P, and 0.64*** for Bray 1-P. There were no obvious turning points in the relationships between Olsen-P, water-soluble P, or $CaCl_2$-P and the amounts of P released from the sandy soils. The release of P from the sandy soils appeared to be controlled by a precipitation–dissolution reaction rather than a P sorption–desorption process. Furthermore, the sequential extraction of soils using deionized water indicated that P released was not limited to the labile P (H_2O-P, $NaHCO_3$-IP) and potentially labile P (NaOH-P) pools, but also from the HCl-P, indicating that all of P fractions except for residual P in the sandy soils can contribute to P release.

Key Words: Phosphorus release potential; Phosphorus fractions; Adsorption; Sandy soil

INTRODUCTION

Phosphorus (P) is generally considered to be the key element that limits freshwater quality and causes eutrophication in many lakes and other water bodies (1–3). Accelerated eutrophication of streams and lakes is one of the greatest challenges facing water quality management. This problem is generally related to increases in the annual input of nutrients to surface water. Consequently, the control of nutrients, especially P, in surface runoff and leaching (subsurface drainage) is considered as the best way to minimize the eutrophication risk (4–6). Increased concentration of dissolved reactive P (DRP) in surface runoff is highly correlated with increased soil test P (STP) levels (7–10). Soils that contain high levels of P due to excessive fertilization can become the primary source of P in runoff (8).

As a result of the continuous rise in soil P levels, agricultural and urban areas increasingly contribute to the eutrophication of surface water by surface runoff and leaching. The loss of P from agriculture to water-courses has increased over the last few decades as a result of increased intensive farming and the development of a more industry-based type of agriculture (11–14). Even though many studies have been conducted on P in the last 20 years, information is still lacking regarding the use of soil P availability indices for environmental risk assessment.

Soil P tests provide farmers with an indicator of how much plant-available P is present in a soil and, consequently, the quantity of nutrients to be applied to obtain desired crop yields. Several studies have demonstrated that the losses of P from soil vary with soil type, tillage, soil moisture content, season, and crop management (2,5,7,15–18). Phosphorus losses by erosion, surface runoff, and leaching or lateral subsurface flow are substantial when soil test P values are above the optimal ranges (7,19,21). Soil P testing is currently used in several countries, including the USA, as a means of identifying areas where applications of P fertilizers and manures should be reduced or eliminated in order to protect water quality (21–24).

Although the total amount of P loaded in surface runoff and stream flow is important to water quality, the forms or fractions of P in soils that are released into the waters are probably more critical. This information is essential if agriculture is to adopt nutrient management plans and recommendations designed to reduce the P load to the surface waters. To predict the transport of P from soils to the environment, key soil chemical processes such as P adsorption–desorption and precipitation–dissolution should also be understood. The objectives of this study were (i) to determine P transport/leaching potential from typical sandy soils under citrus and vegetable production and (ii) to evaluate the relationship between P transport/leaching potential and soil P availability indices and adsorption capacity.

MATERIALS AND METHODS

The soils used in this study, totaling 96 samples, were taken from commercial vegetable farms and citrus groves in Florida. The soils were Wabasso sand (sandy, siliceous, hyperthermic alfic haplaquods), Waveland fine sand (sandy, siliceous, hyperthermic, ortstein arenic haplaquods), Ankona sand (sandy, siliceous, hyperthermic, ortstein arenic haplaquods), Winder variant sand (sandy, siliceous, hyperthermic typic glossaqualfs) and Nettles sand (sandy, siliceous, hyperthermic, ortstein alfic arenic haplaquods). All soil samples were air-dried and ground to pass through a 2-mm sieve. Soil pH was measured in water and KCl solution at a soil : water (solution) ratio of 1 : 1, and electrical conductivity (EC) was measured in water at a 1 : 2 soil : -water ratio using a pH/ion/conductivity meter (Accumet Model 50, Fisher Scientific) (25). The total organic C was determined using a CNS-Analyzer (NA 1500, Fisons Instruments Inc., Dearborn, MI). Particle size distribution of soil samples was determined using a micro-pipette method (26). In general, soils were slightly acidic to slightly alkaline with low organic C, though acidity and organic C varied widely among the soil samples. These soils contained more than $800\,g\,kg^{-1}$ sand, but less than $60\,g\,kg^{-1}$ silt and clay (Table 1).

Table 1. Statistical Summary of Basic Soil Properties and Extractable Phosphorus in the 96 Soil Samples

Properties		Range	Mean	SD[†]
Basic properties	PH (H_2O)	3.92–8.80	6.67	1.27
	PH (KCl)	3.80–8.60	6.34	1.27
	EC ($\mu s\,cm^{-1}$)	52–867	245	160
	Organic C ($g\,kg^{-1}$)	0.5–27.2	4.3	4.1
	Sand ($g\,kg^{-1}$)	788–980	928	36
	Silt ($g\,kg^{-1}$)	1–113	26	21
	Clay ($g\,kg^{-1}$)	8–143	47	24
Extractable P	Olsen-P ($mg\,kg^{-1}$)	1.0–75.2	19.7	16.2
	Mehlich 1-P ($mg\,kg^{-1}$)	1.3–241.2	64.6	71.9
	Water-soluble P ($mg\,kg^{-1}$)	0.8–23.9	7.1	5.4
	0.01 M $CaCl_2$-P ($mg\,kg^{-1}$)	0.1–10.8	2.4	2.1
	Bray-P ($mg\,kg^{-1}$)	0.7–243.1	50.4	5.8
	Mehlich 3-P ($mg\,kg^{-1}$)	5.2–334.6	84.4	91.3

[†]SD: Standard deviation.

Measurement of Soil P Availability Indices

Soil samples were analyzed for P availability indices by six different extraction methods: (i) Olsen-P (1 : 20 ratio of soil to 0.5 M $NaHCO_3$ (pH 8.5), 30-minute reaction time (27)); (ii) Mehlich 1-P (1 : 4 ratio of soil to 0.05 M HCl + 0.0125 M H_2SO_4, 5-minute reaction time (27)); (iii) water-soluble P (1 : 10 ratio of soil to deionized water, 60-minute reaction time (27)); (iv) $CaCl_2$ extractable P (1 : 10 ratio of soil to 0.01 M $CaCl_2$, 60-minute reaction time (27)), (v) Bray 1-P (1 : 7 ratio of soil to 0.03 M NH_4F + 0.025 M HC, 1-minute reaction time (27)), and (vi) Mehlich 3-P (1 : 10 ratio of soil to Mehlich 3 extraction solution, 5-minute reaction time (28)). After each extraction, the suspension was centrifuged at $7500 \times g$ for 30 min and then the supernatant was passed through a Whatman 42 filter paper. Phosphorus concentrations in the extracts from methods (i), (ii), (iii), and (iv) were determined colorimetrically by the molybdenum blue method (29). The P concentrations from methods (v) and (vi) were determined by inductively coupled plasma atomic emission spectroscopy (ICPAES, J-Y Emission Division Instruments SA, Inc., New Jersey).

Phosphate Sorption

Eighty out of the 96 soil samples were selected for measuring P sorption capacity. Phosphorus sorption isotherms were determined as follows: Soils (each 1-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 (180 cycles/min) for 24 h at 25°C. Then the suspensions were centrifuged at $10,000 \times g$ for 10 min and filtered through a Whatman 42 filter paper. Phosphorus concentrations in the filtered solution were colorimetrically determined using the molybdenum blue method. The simple Langmuir equation was employed to describe the P sorption isotherms. The adsorption maximum (Q_m) was obtained from the Langmuir equation. The Langmuir equation is expressed as: $Q = KC\, Q_m/(1 + KC)$, where Q is 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 the constant related to P binding energy.

Fractionation of Soil Phosphorus

Ninety-six soil samples along with 20 soil samples that had been subjected to eight successive extractions with deionized water were used for soil P fractionation. A modified method of Hedley et al. (30) was selected in this study to determine soil P fractions. Soils (each 1-g) were placed into 50-ml centrifuge tubes and were sequentially extracted with 30-ml of deionized water, 0.5 M NaHCO$_3$ (pH = 8.2), 0.1 M NaOH, and 1 M HCl. Each extraction lasted for 16 h on an end-to-end shaker (180 cycles/min). After each extraction, the tubes were centrifuged at $7500 \times g$ for 30 min, the supernatant was then passed through a Whatman 42 filter paper. The P concentrations in the filtrates from deionized water and HCl extractions, and the inorganic P (IP) in the bicarbonate and hydroxide extracts were colorimetrically determined by the molybdenum-blue method. Total P in the bicarbonate and hydroxide extracts was also determined by the molybdenum-blue method after digestion with acidified ammonium persulfate (31). The organic P (OP) concentrations in the bicarbonate and hydroxide extracts were calculated from the difference between the total P and the IP contents in the extracts. Soil total P was determined by the perchloric acid digestion method (27). Residual-P was calculated by subtracting the sum of the above four types of extractable P from the total P content in the soil. The residual P was also measured separately to evaluate the P budget. Based on the sequence of extractions, soil P fractions were referred to as water-soluble P (H$_2$O-P), bioavailable inorganic P (NaHCO$_3$-IP), readily mineralizable organic P (NaHCO$_3$-OP), potentially bioavailable inorganic P (NaOH-IP), potentially bioavailable organic P (NaOH-OP), acid-soluble P (Ca-bound P/HCl-P), and residual P.

Measurement of Phosphorus Release Potential in Soils

Both successive leaching and extraction were conducted to evaluate the P release potential from the soils. Successive leaching measured the slowly

released P, whereas successive extractions would be quantified as rapidly released P from the soils.

Successive Leaching

All of the 96 soil samples were used for the successive leaching experiment. A 50-g sample for each soil was placed onto a Whatman 42 filter paper, then fitted in a funnel, moistened to field capacity, and incubated at room temperature for 2 days. During each leaching event, 50-ml of deionized water were applied. This leaching process was repeated daily for a total of 15 sequential leachings (lasting 15 days). Leachates were collected in 125-ml polyethylene bottles. Phosphorus concentration in each leachate sample was determined using the molybdenum blue method. The amount of P leached was calculated based on the leachate volumes and P concentrations of the leachates.

Successive Extraction

Representative soil samples (20) were selected for the successive extraction experiment. Portions of soil, each containing 1.0-g soil (oven dry basis), were placed into 50-ml centrifuge tubes and extracted with 30-ml of deionized water. This extraction was successively repeated for a total of eight sequential extractions. Each extraction lasted for 16 h on an end-to-end shaker (180 cycles/min). After each extraction, the tubes were centrifuged at $7500 \times g$ for 30 min, and the supernatant was passed through a Whatman 42 filter paper. The P concentrations in the filtrates were determined colorimetrically using the molybdenum-blue method.

Statistical Analyses

Correlations between extractable P, P fractions and the amounts of P released by leaching (or extraction), mean and standard deviation of the extractable P, P fractions, and linear regressions between P released in the leaching and the availability indices of P were conducted using the SAS computer programs (32).

RESULTS AND DISCUSSION

Soil P Availability Indices

The amounts of available P from the 96 soil samples measured by six extraction methods varied greatly (Table 1). The mean value of extractable

Table 2. Correlation Coefficients (r) Among Different P Availability Indices ($n = 96$)

P Indices	Olsen-P	Mehlich 1-P	Water-Soluble P	0.01M CaCl$_2$-P	Bray-P	Mehlich 3-P
Total-P	0.66**	0.83**	0.68**	0.60**	0.54**	0.65**
Olsen-P		0.87**	0.93**	0.87**	0.68**	0.79**
Mehlich 1-P			0.88**	0.75**	0.75**	0.84**
Water-soluble P				0.93**	0.73**	0.81**
0.01 M CaCl$_2$-P					0.56**	0.69**
Bray-P						0.76**

**Significant at < 0.01 level.

P in the soils decreased in the following order for the six different extraction methods: Mehlich 3-P (84.4 mg kg^{-1}) > Mehlich 1-P (64.4 mg kg^{-1}) > Bray-P (50.4 mg kg^{-1}) > Olsen-P (19.7 mg kg^{-1}) > water-soluble P (7.1 mg kg^{-1}) > 0.01 M CaCl$_2$-P (2.4 mg kg^{-1}). Olsen-P, water-soluble P and 0.01 M CaCl$_2$-P accounted for only a small proportion of the total P and were the readily released P pools, whereas Mehlich 1-P, Bray 1-P, and Mehlich 3-P accounted for a large proportion of the total P, and likely represented both the readily and slowly released P pools. However, there were very significant correlations (r) among all the extractable P indices (Table 2). The correlation coefficients (r) among water-soluble P, 0.01 M CaCl$_2$-P, and Olsen-P were 0.87 or higher. Water-soluble P had a significant correlation with other P availability indices, particularly with 0.01 M CaCl$_2$-P and Olsen-P. Therefore, based on these high correlation coefficients, each of the P availability indices could be mutually predicted with a reasonable amount of precision in the sandy soils.

Phosphorus Sorption Capacity

The P adsorption maximum (Q_m) obtained from the Langmuir equation can be used to indicate P sorption capacity of the soils (33). The Q_m values of the 80 sandy soil samples varied from 14.2 to 107.7 mg P kg^{-1} with an average value of 40.4 mg P kg^{-1} (Figure 1). The P adsorption capacities for sandy soils used in this study were much lower than those reported for other soils (34–35). The Q_m was significantly and positively correlated with clay contents ($r^2 = 0.75$**) and poorly correlated with total Fe ($r^2 = 0.25$**) (Figure 1), suggesting that clay content has a great effect on P sorption capacities of these soils. The small P adsorption capacity (Q_m) indicates that these sandy soils may have great potential for P loss into both surface and subsurface waters by leaching or surface runoff.
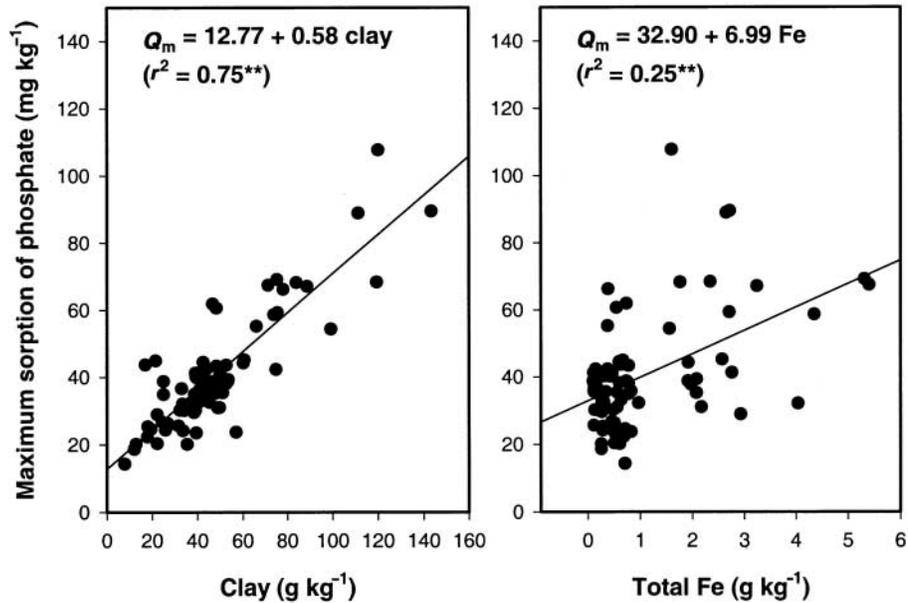
Figure 1. The relationship between maximum sorption of phosphate to clay and total Fe content of soils ($n = 80$).

Phosphorus Fractionation

The concentrations of all P fractions and their percentage in the total P are summarized in Table 3. Sequential extractions of the soils with deionized water, $NaHCO_3$, NaOH, and HCl indicated that most of the P in the soils was extractable to water, mild alkaline, or acid medium. These results indicated that either the concentrations of all the P fractions or the percentage of the total P varied greatly among the 96 soil samples (Table 3). The mean percentages of each P fraction in the total decreased in the following order: residual-P (35.0%) > $NaHCO_3$-TP (24.6%) > NaOH-TP (14.9%) > HCl-P (14.7%) > H_2O-P (10.7%). The percentage of H_2O-P in the total P was the lowest among all the fractions, but the percentage was much higher than in other types of soils such as Mollisols (36). This may imply that P leaching or transport potential is higher in the sandy soils, given the same amount of total P. Correlation coefficients (r) among the fractions and with total P were analyzed. Total P was positively correlated only with the proportions of the $NaHCO_3$-IP ($r = 0.20^*$) and HCl-P ($r = 0.68^{**}$) in the total P, suggesting that P accumulation in the sandy soils by fertilization occurred mainly in the fractions of $NaHCO_3$-IP and HCl-P. The concentrations of all P fractions, except for residual P and NaOH-OP, were significantly correlated with soil P availability indices (Table 4). It appears that most of the P fractions were readily extractable or potentially leachable.

Table 3. Summary of P Fractionation of the 96 Soil Samples

P Fractions	Total-P	H$_2$O-P	NaHCO$_3$			NaOH			HCl-P	Residual-P
			IP[†]	OP	TP	IP	OP	TP		
				Absolute Amount (P, mg kg^{-1})						
Range	23.6–552	0.9–45.5	1.0–141	0–25.9	1.2–150	0.7–52.7	0.0–11.4	2.2–58.1	0.1–162	3.5–338
Mean	144.5	14.0	34.5	3.2	37.7	17.0	2.8	19.8	29.7	43.2
SD[‡]	108.7	11.1	34.8	4.9	37.3	14.6	2.6	15.2	38.5	46.9
				Proportion of the Total P (%)						
Range	100	1.0–28.1	1.3–42.6	0–11.6	1.6–45.6	1.5–48.7	0–10.7	3.5–52.3	0.2–51.0	1.2–89.8
Mean	100	10.7	22.2	2.4	24.6	12.7	2.2	14.9	14.7	35.0
SD		5.6	10.9	3.0	11.7	8.4	2.4	8.4	11.6	21.6

[†]IP—inorganic P; OP—organic P; TP—sum of inorganic and organic P.
[‡]SD: Standard deviation.

Table 4. Correlation Coefficients (r) Between Soil P Fractions and P Availability Indices ($n = 96$)

P Fractions	Olsen-P	Mehlich 1-P	Water-Soluble P	0.01 M CaCl$_2$-P	Bray-P	Mehlich 3-P
H$_2$O-P	0.94**	0.90**	0.98**	0.93**	0.72**	0.80**
NaHCO$_3$-IP[†]	0.93**	0.96**	0.90**	0.79**	0.73**	0.85**
NaHCO$_3$-OP	0.48**	0.37**	0.47**	0.58**	0.23*	0.45**
NaHCO$_3$-TP	0.93**	0.95**	0.90**	0.82**	0.71**	0.86**
NaOH-IP	0.73**	0.81**	0.76**	0.60**	0.76**	0.78**
NaOH-OP	0.21*	0.20	0.15	0.26*	0.07	0.12
NaOH-TP	0.74**	0.81**	0.76**	0.62**	0.74**	0.77**
HCl-P	0.49**	0.72**	0.47**	0.39**	0.36**	0.47**
Residue-P	−0.07	0.11	0.01	0.01	−0.01	0.01

*,**Significant at < 0.05 level and < 0.01 level, respectively.
[†]IP—inorganic P; OP—organic P; TP—sum of inorganic and organic P.

Phosphorus Release Potential

The amounts of P released by the extraction were higher than those obtained by the leaching, and the amounts of P released were time dependent (Figure 2). In the leaching experiment, the amounts of P released during the first leaching ranged from 0.06 to 5.18 mg kg^{-1} and the corresponding values for the second, third, fourth, and 15th (last) leaching were 0.016–5.91, 0.030–3.18, 0.022–3.83, and 0.0010–1.79 mg kg^{-1}, respectively. The amounts of P released during the first extraction with deionized water in the extraction experiment ranged from 5.59 to 49.82 mg kg^{-1}, the corresponding values for the second, third, fourth, and eighth (last) extraction were 2.13–33.6, 1.05–24.0, 0.67–18.8, and 0.48–11.7 mg kg^{-1}, respectively. The total amount of P released during the 15 leachings averaged 10.20 mg kg^{-1}, which amounted to 7.7% of the total P in the soils, whereas application of the successive extraction method with eight extractions released about 39.2% of the total soil P from these soils. For all the soils studied, the amounts of P released were generally greater during the first four leachings or extractions than those released by the subsequent leaching or extraction later on. This may indicate that the release of loosely adsorbed or easily soluble P was a fast reaction, whereas less soluble P fractions were more slowly released. However, the decrease in P release with time was small, even up to the last leaching or extraction, during which considerable amounts of P were released from most of the soils. Phosphorus released from the soils persisted for a long time, but the rate of P release was slower in the soils with smaller amounts of extractable P than in the soils with high amounts of extractable P (data not shown).
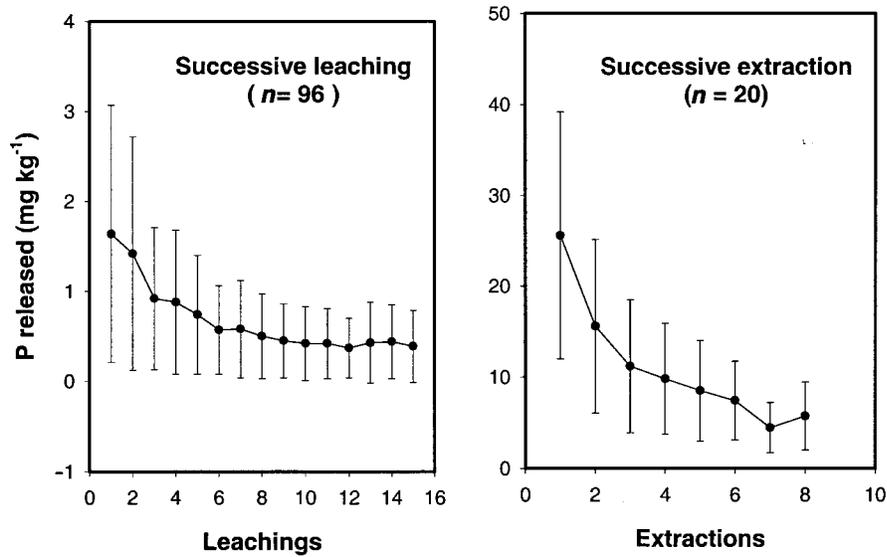
Figure 2. Mean amounts of P released during the 15 leachings and eight extractions. Error bars represent SD.

Phosphorus Release Potential in Relation to Fractions and Availability Indices of Phosphorus

The amounts of P released by the leaching or extraction were significantly correlated with the extractable P and with most of the P fractions, but the correlation coefficients (r) varied among the different P availability indices and P fractions (Table 5). The correlation coefficients (r) generally decreased in the order of water-soluble $P > 0.01$ M $CaCl_2$-P > Olsen-P > Mehlich 1-P > Mehlich 3-P > Bray 1-P > total-P for the P availability indices, and H_2O-P > $NaHCO_3$-TP > $NaHCO_3$-IP > NaOH-TP > NaOH-IP > $NaHCO_3$-OP > HCl-P > NaOH-OP for the P fractions. Among all the P availability indices and P fractions, the water-soluble P, 0.01 M $CaCl_2$-P, Olsen-P, Mehlich 1-P, H_2O-P, $NaHCO_3$-TP, and $NaHCO_3$-IP had the most significant correlations with P release potential ($r > 0.60$**). Therefore, these P availability indices and P fractions could be better indicators of P release potential in the sandy soils. The P pools or fractions were considered to constitute the most mobile P in the sandy soils. Therefore, the P amounts released in water during the extraction were significantly correlated with the P indices or P fractions. These results are consistent with previous reports. For example, Heckrath et al. (1995) reported that P losses in drainage water were closely related to soil Olsen-P (19). Also, Pautler and Sims (2000) reported that Mehlich 1-P could be used to predict the concentrations of desorbed P (strip-P) with reasonable accuracy (24).

Table 5. Correlation Coefficients (*r*) Between the Amounts of P Released During Successive Leaching or Successive Extraction and Various P Availability Indices

P Forms		Successive Leaching ($n = 96$)		Successive Extraction ($n = 20$)	
		The First Leaching	Total of 15 Leachings	The First Extraction	Total of 8 Extractions
P availability indexes	Olsen-P	0.84**	0.94**	0.97**	0.96**
	Mehlich 1-P	0.80**	0.86**	0.91**	0.95**
	Water-soluble P	0.92**	0.97**	0.99**	0.98**
	0.01 M CaCl$_2$-P	0.90**	0.96**	0.95**	0.94**
	Bray-P	0.60**	0.64**	0.65**	0.67**
	Mehlich 3-P	0.70**	0.77**	0.88**	0.90**
P fractions	H$_2$O-P	0.92**	0.97**	0.99**	0.98**
	NaHCO$_3$-IP[†]	0.81**	0.89**	0.96**	0.97**
	NaHCO$_3$-OP	0.44**	0.50**	0.15	0.14
	NaHCO$_3$-TP	0.81**	0.90**	0.95**	0.96**
	NaOH-IP	0.63**	0.68**	0.85**	0.89**
	NaOH-OP	0.13	0.21*	−0.49*	−0.49*
	NaOH-TP	0.63**	0.69**	0.82**	0.86**
	HCl-P	0.43**	0.49**	0.27	0.32
	Residue-P	−0.05	−0.01	−0.19	−0.18
	Total-P	0.59**	0.68**	0.55*	0.58**

*,**Significant at < 0.05 and < 0.01, respectively.
[†]IP—inorganic P; OP—organic P; TP—sum of inorganic and organic P.

Correlation analyses revealed that the amounts of P released from the soils may have been affected by the P adsorption capacity of the soils, but the correlation coefficients between maximum adsorption of P and the amounts of P released in the first leaching ($r = −0.27$**) and the total amount of P released during the 15 leachings ($r = −0.29$**) were low. The low correlation coefficient values between maximum adsorption of P and the amounts of P released suggested that P release in the sandy soils is not controlled by adsorption–desorption processes, but by dissolution–precipitation reactions, as evidenced by the long lasting, but slow release feature (Figure 2).

Phosphorus losses by erosion, surface runoff, or subsurface flow have been reported to sharply increase with soil P availability indices when the extractable P values are above critical levels (changing points) (7,16,19). Hesketh and Brookes (2000) found that the critical levels measured by extraction with CaCl$_2$ varied widely between soils, from 10 to 119 mg Olsen-P kg^{-1} (17). However, our data failed to suggest this changing point between the Olsen-P and the amounts of P released, extractable P values, or P fractions in the sandy soils. The amount of P released increased

linearly with Olsen-P (Figure 3). Therefore, it appears likely that release of P in the sandy soils was mainly controlled by a dissolution reaction of P-minerals rather than a P sorption–desorption mechanism.

The changes in the P fractions of 20 soil samples after eight successive extractions are presented (Table 6). After eight successive extractions with deionized water, soil samples showed a sharp reduction in H_2O-P, $NaHCO_3$-P, and to a lesser extent, a reduction in NaOH-P, but no change occurred in the residual-P (Table 6). The H_2O-P and $NaHCO_3$-P likely contributed the most to the P release potential followed by the NaOH-P and the HCl-P in the leaching trials. The reduction in HCl-P after successive extractions with water indicates that a part of the relatively stable Ca-bound P in the sandy soils was dissolved.
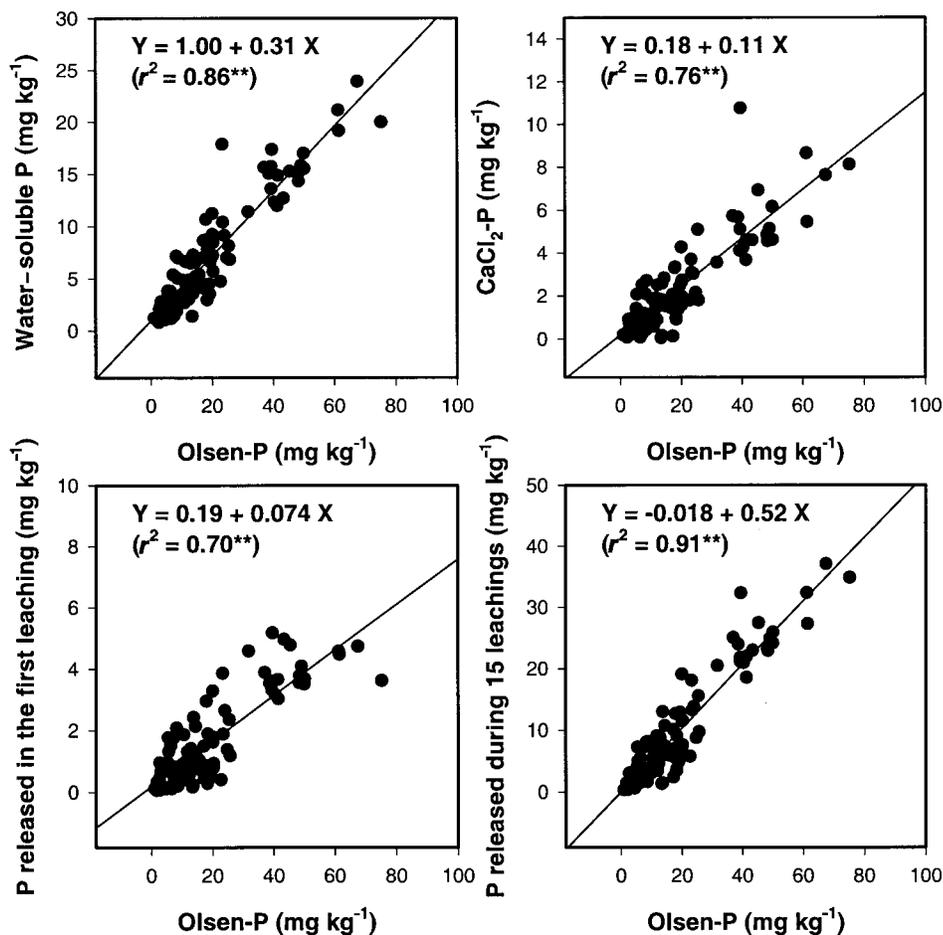
Figure 3. Relationships between Olsen-P and water-soluble P, $CaCl_2$-P, or amount of P released during the first leaching and total amount of P released during 15 leachings ($n = 96$).

Table 6. Changes in Phosphorus Fractions of Selected Soils After Eight Successive Extractions ($n = 20$)

P Fractions		Total-P	H_2O-P	$NaHCO_3$-P	NaOH-P	HCl-P	Residual-P
Amounts (mg kg^{-1})	Before extraction	293 ± 124	24.7 ± 12.9	79.8 ± 45.9	34.4 ± 16.8	78.1 ± 46.4	75.9 ± 26.3
	After extraction	198 ± 112	5.7 ± 3.7	31.7 ± 19.9	25.4 ± 15.4	63.7 ± 48.0	71.8 ± 76.4
Percentage (%)	Before extraction	100	8.6 ± 3.0	28.1 ± 12.0	12.3 ± 4.1	24.6 ± 11.2	26.3 ± 18.0
	After extraction	100	3.0 ± 1.6	17.4 ± 9.7	14.2 ± 7.4	28.4 ± 15.1	37.0 ± 24.7

CONCLUSIONS

This study indicated that the sandy soils characteristically had high proportions of H_2O-P in the total P as well as low adsorption capacity, and it revealed that P in these sandy soils is readily leached. Phosphorus release potential in the sandy soils was positively correlated with all the P availability indices and P fractions, except for the residual P, and increased linearly with extractable P levels. No obvious changing point existed between the amount of P released and the extractable P. All soil P fractions can contribute, to a varying degree, to the P release during leaching. The results from this study suggest that water-soluble P, $CaCl_2$-P, and Olsen-P are the best P availability indices for predicting P release potential in these sandy soils, although all the P availability indices were more or less correlated with the amounts of P released.

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