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ORIGINAL ARTICLE

Effects of soil aggregate size on phosphorus extractability and uptake by rice (*Oryza sativa* L.) and corn (*Zea mays* L.) in two Ultisols from the Philippines

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Abstract

A number of recent studies suggest that soil aggregation may affect short- and long-term phosphorus (P) availability in highly weathered soils. We investigated the effect of natural soil aggregate sizes (from < 0.212 to 4–5.6 mm) on P extractability and plant P availability in low-P and high-P Siniloan soils (Typic Palehumults) from Laguna, Philippines. Mehlich-1 extractable P was always greatest in the smallest aggregates, regardless of whether or not it was extracted without P addition or extracted after 15 days incubation with newly applied P in both intact and ground aggregates. Grinding significantly increased the initial extracted P only in high-P soil. Soil aggregate size had little effect on the extractability of newly added P because the short-term Mehlich-1 P buffering coefficient (PBC), a change in Mehlich-1 extracted P (mg kg^{-1} soil) per unit of added fertilizer P (mg kg^{-1} soil), was not significantly correlated with aggregate size. In the greenhouse experiment, plant growth (shoot dry weight, root length and dry weight) and total P in the shoots of both corn (*Zea mays* L.) and rice (*Oryza sativa* L.) were markedly increased with decreasing aggregate diameters from 4–5.6 mm to < 0.212 mm, even when the plant had adequate P in the rice experiment in the high-P soil. There was no interaction between P supply and aggregate size on the plant growth response and P uptake in both rice and corn grown in the two soils, suggesting that the effect of soil aggregation on plant P availability of newly added P was small. Although, the smaller aggregates themselves also contained higher total P, finer and longer root growth in these aggregates as a direct effect of aggregate size on root growth mainly contributed to better plant growth and P uptake in these aggregates. The findings of this study suggest that in Siniloan soil, soil aggregation had little effect on short-term PBC and plant P availability of the P newly added to soil over 5 weeks. However, in high-P soil, the current soil test procedures, which require grinding and shaking of soil sample, might overestimate the available P status of the soil.

Key words: phosphorus extractability, plant phosphorus availability, soil aggregate size.

INTRODUCTION

Phosphorus (P) is one of the major nutrients limiting agricultural production in many highly weathered soils in the tropics. These soils often have low available P because of high P retention by Al and Fe oxides and amorphous materials (Fox and Searle 1978; Sanchez and Uehara 1980; Wang *et al*. 2001). The amount of P fertilizer needed depends not only on the crop P requirement, but also on the amount of extractable soil P and the P fixing capacity of the soil. Accurate assessment of P availability in soils and precise prediction of P fertilizer requirements is increasingly important to sustainable agriculture and to protecting the environment from the detrimental effect of excess P (Wang *et al*. 2001). A P decision support system (PDSS) for managing P in acid

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tropical upland soils has been developed. However, estimation of the crop P fertilizer requirement of the PDSS using the buffer coefficient, the soil critical level of extractable P and the current extractable P level is usually accompanied by errors caused by uncertainties in critical soil test levels and the buffering coefficient (Chen *et al.* 1997; Dobermann *et al.* 2002). Recent studies (Linquist *et al.* 1997; Wang *et al.* 2001) have provided evidence that soil aggregate size influences P sorption and bioavailability in highly weathered soils (Ultisols, Oxisols). Linquist *et al.* (1997) reported that P sorption in Haiku clay (Typic Palehumult) increased as aggregate size decreased, and larger soil aggregates with relatively less surface area than smaller aggregates may reduce P fixation and result in increased availability of recently applied P. Using a soil column leaching method in Leilehua, an Ultisol, Wang *et al.* (2001) reported that after 28 days of incubation of separated aggregate size fractions with newly added P, P desorption was greater from the large aggregates (4–6 mm) than from the small aggregates (< 0.5 mm). In their pot experiment on two Oxisols (Kappaa and Wahiawa series) and on an Ultisol (Leilehua series), plant growth and P uptake of soybean (*Glycine max* L. Merr.) and lettuce (*Lactuca sativa* L.) in the large aggregates were higher than in the small aggregates after equal amounts of P were added to the separated aggregate fractions. These researchers concluded that aggregation affects short-term and long-term plant P availability, and suggested that considerations of the aggregate effect may improve the relationship between extractable P, P supply and crop yield and eventually improve the precision of P diagnosis and recommendations on well-aggregated soils (Wang *et al.* 2001). However, a previous study by Lima and Anderson (1997) showed that the larger aggregates (1–2 mm) from an A horizon in Oxisol contained more clay, goethite and extractable Fe and Al than the smaller aggregates (0.1–0.2 mm) and, therefore, the larger aggregates could adsorb more P than the smaller aggregates. A number of other studies on nutrient uptake with aggregates of varying sizes (Cornforth 1968; Wiersum 1962) have indicated that P uptake from the small aggregates is higher than that from the large aggregates. As P is relatively immobile in soils, and roots can deplete P only from a distance that coincides approximately with the length of the root hair, P located inside large aggregates may not be accessible to roots growing around them (Misra *et al.* 1988). However, Linquist *et al.* (1997) showed that freshly applied P may be initially adsorbed to only a thin surface layer of the aggregates and, therefore, smaller aggregates with a larger outer surface area might have higher P sorption; hence, less availability of recently applied P.

If soil aggregation plays an important role in P sorption and P availability in highly weathered soils, little is known about the effect of natural soil aggregation on P extractability and plant P availability across a range of soil types. In addition, the current soil P test methodology, which requires grinding and vigorous shaking of soil samples in the extractant may be of limited value for predicting P fertilizer requirements because of destruction of the soil aggregates. A better understanding of the relationship between soil aggregate size and P sorption, P extractability and plant P availability will refine the current soil P tests and fertilizer P recommendation procedures.

The objectives of this study were to examine the effects of natural soil aggregate size on the current extractable P, the P buffering coefficient and plant P availability in two Ultisols with a different P fertilizer history. Rice (*Oryza sativa* L.) and corn (*Zea mays* L.) were used as test crops because they have different root systems, which may present different potential to penetrate and explore P from soil.

MATERIALS AND METHODS

Soil samples and fractionation

Soil samples with different P histories were collected from a long-term (5 years) P experimental field in Siniloan, Laguna, Philippines. The experiment used a rice–legume cropping system with different levels of P addition. Other fertilizers were applied as needed. The soil at Siniloan is classified as a Typic Palehumult. Soil samples were collected from plots that had never received P fertilizer (low-P soil) and from plots that had received an accumulated amount of 472 kg P ha^{-1} (high-P soil) during the experiment. After air-drying in a shaded area, six aggregate size fractions of < 0.212, 0.2–0.5, 0.5–0.1, 1–2, 2–4 and 4–5.6 mm from each soil were obtained using a Ro-tap shaker model RX-29–16 (WS Tyler, Mentor, OH, USA) (dry-sieving method). The corresponding mean aggregate diameter (MAD) used to identify each fraction was 0.106, 0.35, 0.75, 1.5, 3.0 and 4.8 mm, respectively.

In both soils the aggregate size fractions of 3.0 and 1.5 mm were dominant and they accounted for 62.4% (low-P soil) to 64.9% (high-P soil) of the total soil mass. The smallest aggregate (0.106 mm) accounted for only 2.7% in both soils (data not shown). The characteristics of the aggregate size fractions from the soils are presented in Table 1.

Extractable P determination

The current or initial extractable P using the Mehlich-1 method (Nelson *et al.* 1953) was extracted from whole soil and six aggregate size fractions (4.8, 3, 1.5, 0.75, 0.35 and 0.106 mm) in low-P and high-P soils by shaking

Table 1 Selected soil properties of the aggregate fraction and the whole soil (non-sieved soil) across the two soils

	MAD (mm)							LSD	Whole soil	
Properties	Whole	0.106	0.35	0.75	1.5	3.0	4.8	(0.05)	Low-P	High-P
Bulk density (g cm^{-3})	0.93	0.91	0.90	0.90	0.89	0.89	0.89	0.016	0.937	0.924
pH_{H2O}	4.6	4.7	4.6	4.6	4.6	4.6	4.6	–	4.5	4.6
pH_{KCl}	3.6	3.7	3.6	3.6	3.6	3.6	3.6	–	3.6	3.6
Organic carbon (%)[†]	2.38	2.75	2.57	2.34	2.33 d	2.29	2.32	0.053	2.2 B	2.57 A
Total N (%)[‡]	0.245	0.270	0.260	0.247	0.241	0.245	0.244	0.010	0.235 B	0.256 A
Clay (%)[§]	52.8	44.2	49.7	52.4	53.3	53.7	53.6	1.584	52.74	52.87
Exchangeable acidity (cmolc kg^{-1})[¶]	3.64	3.19	3.67	3.64	3.74	3.87	4.01	0.191	3.87 A	3.41 B
Exchangeable Al (cmolc kg^{-1})[¶]	2.75	2.09	2.66	2.72	2.73	2.92	3.11	0.16	2.93 A	2.58 B
Fe (%)[††]	1.68	1.59	1.60	1.62	1.64	1.66	1.71	0.051	1.69	1.68
Total P (g kg^{-1})[‡‡]	1111	1201	1150	1116	1126	1096	1086	71.4	902	1320

[†] Modified Walkley–Black procedure (Nelson and Sommers 1982). [‡] Digestion method and distillation (Bremner and Mulvaney 1982). [§] Pipette method (Gee and Bauder 1986). [¶] KCl extraction method (Thomas 1982). [††] Acid ammonium oxalate method (McKeague and Day 1966). [‡‡] Perchloric acid digestion (Olsen and Sommers 1982). With the mean aggregate diameter (MAD), the rows without a least significant difference (LSD) value indicate that the *F*-test was not significant at $P < 0.05$. With the whole soil, means followed by different letters within rows are significantly different at $P < 0.05$ using an LSD test.

3 g soil samples in 30 mL of 0.05 mol L^{-1} HCl + 0.0125 mol L^{-1} H_2SO_4 extractant for 5 min, and P in the filtrate was determined colorimetrically (Murphy and Riley 1962). Two sets of aggregate samples were used: (1) aggregate and whole soil samples that were ground and passed through a 2-mm sieve (ground samples), (2) unground aggregate and whole soil samples (intact samples). The same Mehlich-1 method for P extraction was used for both soil sample sets except that the shaking speed was 180 rpm for the ground samples and 50 rpm for the intact samples to keep the intact aggregates from breaking down. All treatments were replicated twice.

Phosphorous buffering coefficient of different aggregates

To estimate the phosphorous buffering coefficient (PBC), three sets of soil aggregate samples were used: (1) ground samples, (2) intact samples, (3) 4.8-mm aggregate fraction pulverized to pass through a 0.2-mm sieve (4.8 mm pulv.). The PBC was determined using a modified wet-to-dry incubation procedure (Sobral *et al.* 1998). For intact samples, 3 g of each sample was first moistened by spraying with 0.01 mol L^{-1} $CaCl_2$ to maintain ionic strength and to avoid breaking the aggregates when the P solution was added. Seven P levels of 0, 15.5, 31.0, 46.5, 62.0, 93.0 and 248.0 mg P kg^{-1} soil were gently added to each aggregate fraction at a soil : P solution ratio of 1:2 to ensure that the soil sample was completely submersed in the P solution. Two drops of toluene were added to inhibit microbial activity. The soil samples were then incubated at 30°C for 15 days until dry. The air-dried, incubated soil samples were then extracted for Mehlich-1 P as described above with a gentle shaking speed of 50 rpm for 5 min to prevent the aggregates from breaking down. All treatments were replicated twice. The PBC, the change in extractable P per unit of P added, was determined by regressing the Mehlich-1P on the rate of P added.

For the ground and 4.8 mm pulv. samples, the same procedure was used except that after adding the P solution the soil samples were shaken at 100 rpm for 6 h in a rotary shaker before incubation. Mehlich-1 P was determined after incubation with a shaking speed of 180 rpm instead of 50 rpm.

Pot experimental design and cultivation

Two experiments using the same procedure, one with corn cv. CAR 818 and the other with upland rice cv. IR55423–01, were conducted. The experiments were done in a split-plot design with four replications. Low-P and high-P soils served as the main plot. The combinations of P-rate (0, 20, 60 and 120 kg ha^{-1}, which was converted to mg P pot^{-1} using a bulk density of the whole soil of 0.93 g cm^{-3}) and aggregate size (0.106, 0.35, 1.5, 4.8 mm and whole soil) served as the subplot. To minimize aeration problems in smaller aggregates, a round, flat clay pot (12 cm in diameter, 6 cm in depth and with a bottom thickness of 0.7–0.8 cm) was used and the soil in the pot was kept approximately 4 cm high; thus, increasing the exposure of soil to the air. Before being placed into the clay pot, the soil samples for each pot (400 g pot^{-1}) were separately spread in a rectangular tray (40 cm long and 30 cm wide) and 80 mL of the corresponding P solution (KH_2PO_4 solution) was applied equally using a sprayer. The K applied to each plot was adjusted to the same level using K_2SO_4. Pots were rotated within a replication every week during the experiment.

Two-day-old seedlings (four for corn and 10 for rice) were planted in each pot and thinned to two plants for corn and five plants for rice per pot at 3 days and 5 days after planting for corn and rice, respectively. To prevent algal growth and to minimize evaporation of water from the soil, when the plants were 6 days old (corn) and 9 days old (rice) each pot was covered with catolina paper cut into a shape that fitted the pot and plate below. Water and other essential nutrients except for P were supplied sufficiently to the plates for plant growth throughout these experiments. The accumulated amounts of the nutrients applied for corn were (mg pot^{-1}): N, 750; K, 720; Ca, 120; Mg, 84; Fe, 45; Zn, 20, and for rice the amounts were the same except that N and K were 480 and 450 mg pot^{-1}, respectively.

To assess the change in extractable P in soil without plants, an additional 80 pots underwent the same procedure as that described in the above experiments except that no crop was planted. These pots were arranged in a completely randomized design in the greenhouse with two replications.

Sampling and analysis

Plants were harvested when they were 32-days old (corn) and 37-days old (rice). Plant shoots were oven-dried at 75°C and weighed. Dried, ground shoot samples were analyzed for total P content by wet digestion (sulfuric-hydrogen peroxide) and colorimetrically measuring P (Murphy and Riley 1962). Roots were collected by carefully separating them from the soil and washing them in water. Total root length (m) was measured using a COM-AIR root-length scanner (Tenix Defence system, Melbourne, Australia). After scanning, the roots were oven-dried at 75°C and weighed. The total root length and root dry weight of plants were determined only in low-P soil at P treatments of 0 kg P ha^{-1} (low-P soil-P1) and 120 kg P ha^{-1} (low-P soil-P4), and in high-P soil at P treatments of 120 kg P ha^{-1} (high-P soil-P4) for both the corn and the rice experiments. Low-P soil-P1, low-P soil-P4 and high-P soil-P4 were representative of low-P, medium-P and high-P levels, respectively.

Soil samples were taken from the pots both before planting (after P fertilization) and after harvesting and air-dried for extractable P analysis.

Statistical analysis

Using PROC GLM of SAS version 6.12 (SAS Institute, Cary, NC, USA), an ANOVA was conducted to assess the differences among the treatments. All parameters were analyzed with corresponding experimental design, except for the analyses of root length and root dry weight; a randomized complete block design was used here because variation of the position in the greenhouse had little effect on plant growth. The relationship between PBC and MAD was fitted using a linear regression model.

RESULTS

Effect of aggregate size on initial extractable P

For both low-P and high-P soils, less P was extracted from larger aggregates than from smaller aggregates, even in ground samples (Table 2). Melich-1 extractable P in the smallest 0.106 mm aggregate fraction was approximately 184% and 50% higher than that of the largest 4.8 mm aggregate fraction in the low-P and high-P soils, respectively. Grinding and vigorous shaking of the aggregates tended to increase extractable P in the large aggregates. However, the increase in extracted P by grinding and vigorous shaking was very small in the low-P soil, for example, this value for the largest aggregate fraction was 0.17 mg P kg^{-1} soil for low-P soil and 2.14 mg P kg^{-1} soil for high-P soil.

Phosphorus buffer coefficient of different aggregate fractions

After the same amounts of P were added separately to aggregate fractions and subjected to 15 days incubation in the laboratory, Mehlich-1 extractable P also consistently increased as aggregate size decreased from 4.8 mm to 0.106 mm in both soils (Fig. 1). This trend was the

Table 2 Effect of aggregate size on initial Mehlich-1 extracted P (mg kg^{-1})

	Low-P soil			High-P soil		
Aggregate size (mm)	Ground	Intact	Mean	Ground	Intact	Mean
Whole soil	2.16	2.02	2.09 d	26.65	25.30	25.98 bc
0.106	4.73	4.76	4.75 a	37.14	36.78	36.96 a
0.35	2.62	2.56	2.59 b	28.46	27.08	27.77 b
0.75	2.32	2.44	2.38 c	26.91	25.55	26.23 bc
1.5	2.13	2.00	2.07 d	26.06	24.06	25.06 c
3.0	2.09	1.85	1.97 d	26.37	23.58	24.98 c
4.8	1.75	1.58	1.67 e	25.76	23.62	24.69 c
Means	2.54 A	2.46 A		28.19 A	26.57 B	

Means followed by the same capital letter (within rows) and the same small letter (within columns) are not significantly different at $P < 0.05$ using a least significant difference (LSD) test.

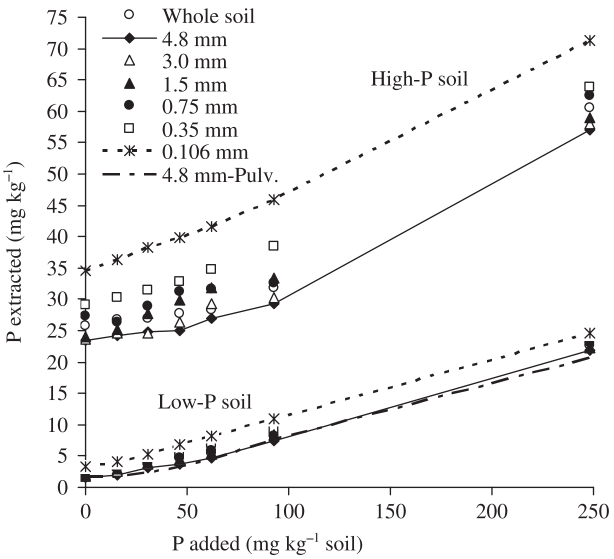

Figure 1 Effect of intact aggregates on Mehlich 1-extracted P at different levels of added P after 15 days incubation in the laboratory.

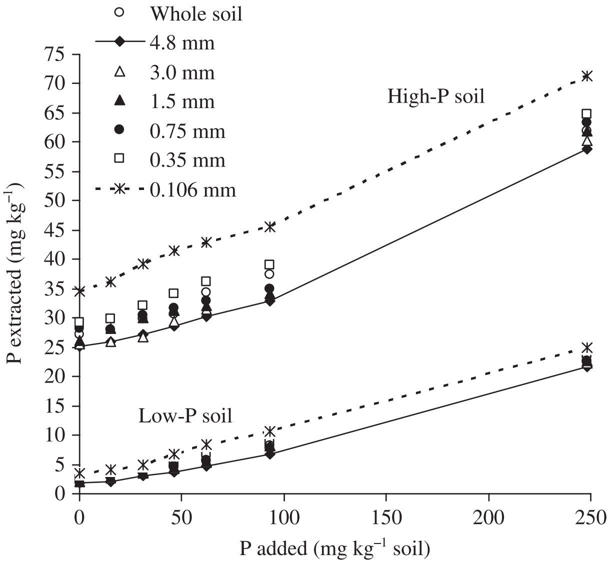

Figure 2 Effect of ground aggregates on Mehlich 1-extracted P at different levels of added P after 15 days incubation in the laboratory.

same whether the aggregates were ground or unground (Fig. 2). Grinding and vigorous shaking of the aggregates had little affect on the recovery of added P using the Mehlich-1 extraction method. When the 4.8 mm aggregates of low-P soil were very finely ground to pass through a 0.2-mm sieve (4.8 mm pulv.), the recovery of newly added P in the 4.8 mm-pulv. was not significantly different from that of the intact 4.8 mm aggregates (Fig. 2).

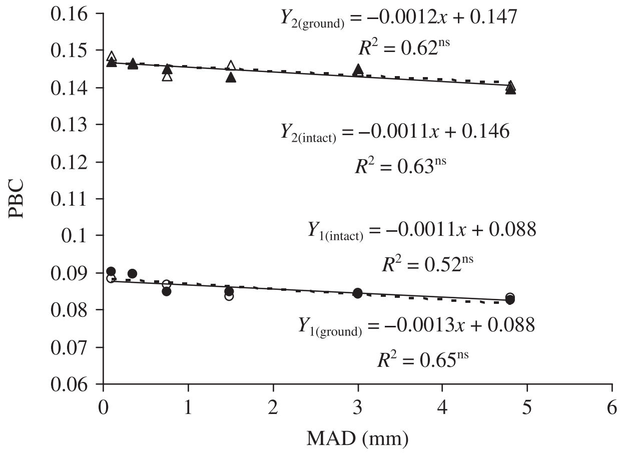

Figure 3 Regression of linear Mehlich-1 phosphorus buffer coefficient (PBC) versus mean aggregate diameter (MAD). Y_1 and Y_2 represent low-P soil and high-P soil, respectively. △ and O with dot lines represent intact samples in high-P and low-P soils, respectively; ▲ and ● with continuous lines represent ground samples in high-P and low-P soils, respectively.

The short-term PBC, the increase in Mehlich-1 extractable P (mg kg^{-1} soil) per unit of applied P (mg kg^{-1} soil) after 15 days incubation, tended to slightly decrease with increasing aggregate size from 0.106 mm to 4.8 mm in both intact and ground aggregates for both soils. However, the decrease was very small and was not significant in either soil (Fig. 3). Grinding and vigorous shaking of the aggregates also had a very small influence on PBC in both soils (Fig. 3).

Effect of aggregate size on plant growth and phosphorus uptake

Plant growth (shoot dry weight) and the total P content of shoot and root growth of corn and rice were significantly influenced by aggregate size and P additions (Table 3, Figs 4–7). There were no interactions between P addition and aggregate size for plant growth response and P uptake in both rice and corn (Table 4).

Shoot dry weight and total P uptake of corn and rice were markedly increased with decreased aggregate sizes in both low-P and high-P soils. The increase in shoot dry weight of plants grown in 0.106 mm aggregates compared with 4.8 mm aggregates was approximately 39% (low-P soil) and 25% (high-P soil) for corn plants, whereas it was approximately 31% and 36% for rice plants (Table 3). Total P uptake in shoots followed the same trend, being 40% (low-P soil) and 22% (high-P soil) higher in 0.106 mm aggregates than in 4.8 mm aggregates for corn plants, and approximately 23% and 28% for rice plants in low-P and high-P soils, respectively (Table 3). The growth of rice only responded to P rates in low-P soil and did not respond to P rates in

Table 3 Shoot dry weight (g pot^{-1}), P uptake (mg pot^{-1}) and P efficiency (mg P g DW^{-1}) of corn and rice at different rates of P and aggregate sizes on low-P soil and high

	Corn						Rice					
	Low-P soil			High-P soil			Low-P soil			High-P soil		
Treatments	SDW	P-up	P-eff	SDW	P-up	P-eff	SDW	P-up	P-eff	SDW	P-up	P-eff
Aggregate size (mm)												
W-Soil	3.85 bc	4.59 bc	1.19	6.99 c	14.09 cd	2.02	3.16 c	3.69 bc	1.17	4.15 c	7.56 cd	1.82
0.106	4.67 a	5.76 a	1.23	8.47 a	16.50 a	1.95	3.81 a	4.21 a	1.11	5.32 a	9.20 a	1.73
0.35	4.12 b	4.93 b	1.20	7.48 b	15.10 b	2.02	3.46 b	3.85 ab	1.11	4.69 b	8.40 b	1.79
1.5	3.66 c	4.41 bc	1.20	6.95 c	14.15 c	2.04	3.18 c	3.71 bc	1.17	4.09 cd	7.62 c	1.86
4.8	3.36 d	4.12 c	1.23	6.78 c	13.49 d	1.99	2.90 d	3.41 c	1.18	3.90 d	7.17 d	1.84
P-rate (mg kg^{-1} soil)												
0	2.80 D	2.89 C	1.03 C	6.84 D	13.38 C	1.96 B	2.55 D	2.48 C	0.97 C	4.32 B	7.83 B	1.81 A
15.2	3.18 C	3.43 C	1.08 BC	7.15 C	13.75 C	1.92 B	2.90 C	2.82 C	0.97 C	4.43 AB	7.79 B	1.76 A
45.5	4.27 B	5.06 B	1.19 B	7.52 B	15.07 B	2.00 AB	3.70 B	4.37 B	1.18 B	4.42 AB	7.87 B	1.78 A
90.9	5.48 A	7.67 A	1.40 A	7.83 A	16.48 A	2.10 A	4.05 A	5.47 A	1.35 A	4.55 A	8.48 A	1.86 A

SDW, shoot dry weight; P-up, P uptake; P-eff, P efficiency; W-Soil, whole soil.
Means followed by the same small letters or the same capital letters within columns are not significantly different at $P < 0.05$ using a least significant difference (LSD) test. An absence of letters indicates a non-significant F-test ($P<0.05$).

Table 4 ANOVA table for shoot dry weight (DW, g pot^{-1}) and total P (mg pot^{-1}) in shoots of corn and rice as influenced by P-rate and soil aggregate size (Size)

		F-test values			
		Corn		Rice	
Treatments	Df	Shoot DW	P content	Shoot DW	P content
Rep	3	0.74^{ns}	0.69^{ns}	0.31^{ns}	0.96^{ns}
Soil	1	4193.10**	9992.2**	1135.16**	2050.76**
P-rate	3	157.35**	152.75**	64.04**	80.68**
Soil x P-rate	3	36.51**	7.00**	40.40**	36.09**
Size	4	65.00**	31.33**	72.98**	28.53**
Soil x Size	4	2.86*	3.02*	5.01**	6.04**
P-rate x Size	12	0.88^{ns}	0.42^{ns}	0.44^{ns}	0.13^{ns}
Soil x P-rate x Size	12	0.34^{ns}	0.25^{ns}	0.29^{ns}	0.09^{ns}

* $P < 0.05$. ** and $P < 0.01$. ^{ns}, not significant at $P < 0.05$.

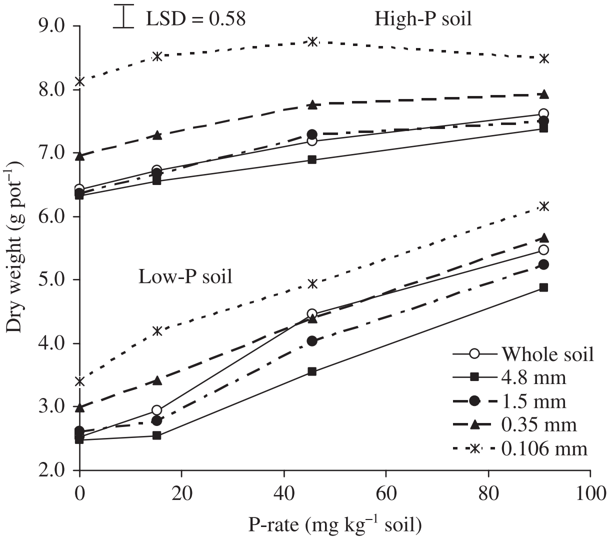

Figure 4 Effect of aggregate size on the shoot dry weight of corn. Error bar represents one least significant difference (LSD) at $P < 0.05$.

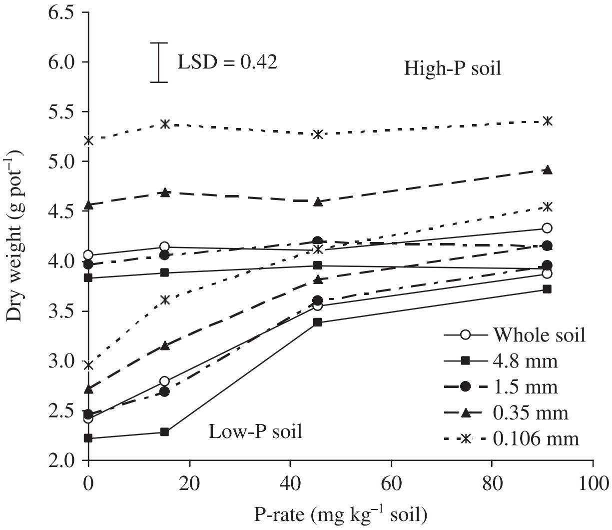

Figure 5 Effect of aggregate size on the shoot dry weight of rice. Error bar represents one LSD at $P < 0.05$.

high-P soil (Table 3, Fig. 5), indicating that P was not a limiting factor for rice in high-P soil. The growth and P uptake of rice, however, still consistently increased with decreased aggregate size in this soil.

Total root length and root dry weight of both corn and rice significantly increased with decreasing aggregate size (Table 5). Plants grown in the smallest aggregate fraction had root lengths approximately 63% (for corn) and 39% (for rice) higher than those of plants grown in the largest aggregate fractions, whereas the root dry weight was only approximately 14% (for corn) and 16% (for rice) higher. The ratio of root length to root dry weight (RL/RDW) of both corn and rice grown in the smaller aggregate size was significantly higher than in the larger aggregate size. This indicated that the roots of plants grown in the smaller aggregates were finer. By naked eye, it was observed that the roots did not grow through, but only around, the aggregates and the roots of plants grown in the larger aggregates tended to be thicker, less branched and shorter compared with those grown in smaller aggregate size fractions. The ratios of root dry weight to shoot dry weight (R/S) for both corn and rice also significantly decreased with decreasing aggregate size (Table 5).

Available P before and after cultivation

Mehlich-1 extractable P was higher in the smaller aggregate fractions in all cases (before planting, after no planting and after the harvest of corn and rice) for both low-P and high-P soils (Table 6), indicating that there could be more available P in the smaller aggregates in all situations.

Table 5 Root growth of corn and rice in response to P levels and aggregate sizes

Treatments	Corn Root length (m pot^{-1})	Corn Root DW (g pot^{-1})	Corn RL/RDW ratio	Corn R/S ratio	Rice Root length (m pot^{-1})	Rice Root DW (m pot^{-1})	Rice RL/RDW ratio	Rice R/S ratio
Aggregate size (mm)								
Whole soil	243.9 c	2.164 b	112.38 d	0.43 a	244.6 c	0.962 c	253.54 c	0.27 ab
0.106	338.7 a	2.296 a	147.26 a	0.38 c	298.3 a	1.045 a	284.31 a	0.25 b
0.35	296.6 b	2.170 b	137.31 b	0.41 b	272.2 b	1.003 ab	270.04 b	0.26 ab
1.5	255.7 c	2.116 bc	120.63 c	0.43 a	244.2 c	0.932 c	260.49 bc	0.27 ab
4.8	207.7 d	2.023 c	102.81 e	0.44 a	215.1 d	0.902 c	236.18 d	0.28 a
P level								
Low-P soil – P1	170.4 C	1.269 C	133.60 A	0.46 A	196.6 C	0.806 C	243.16 C	0.32 A
Low-P soil – P4	294.8 B	2.373 B	123.57 B	0.44 B	261.0 B	1.003 B	259.88 B	0.25 B
High-P soil – P4	340.4 A	2.820 A	120.50 B	0.36 C	307.1 A	1.097 A	279.69 A	0.24 C

DW, root dry weight; RL/RDW, ratio of root length to root dry weight; R/S, ratio of root dry weight to shoot dry weight. Means followed by the same small letters or the same capital letters within columns are not significantly different at $P < 0.05$ using a least significant difference (LSD) test.

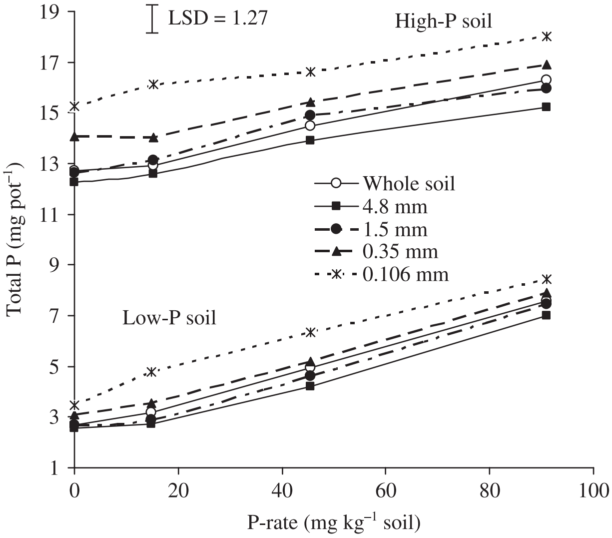

Figure 6 Effect of aggregate size on total P in shoots of corn. Error bar represents one least significant difference (LSD) at $P < 0.05$.

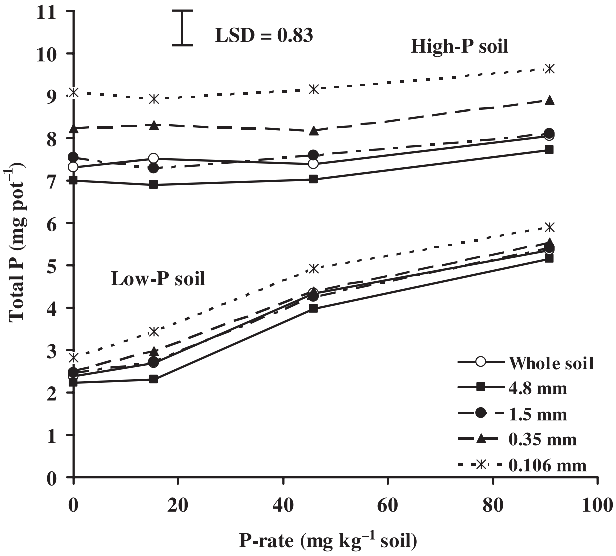

Figure 7 Effect of aggregate size on total P in shoots of rice. Error bar represents one least significant difference (LSD) at $P < 0.05$.

DISCUSSION

Initial extractable P as influenced by soil aggregate size

Initial Melich-1 extractable P (without adding P) increased substantially with decreasing aggregate size in both low-P and high-P soils. This trend was unaffected by the grinding of soil samples for extraction (Table 2). The results suggest that factors other than the exposed surface area contribute to the differences in extractable P among aggregates. The higher initial extracted P in the smaller aggregates could be accounted for by their higher total P and lower clay content, active Fe and exchangeable Al (Table 1). The same result was obtained by Moura and Boul (1976) on Oxisol using the dilute acid extractant method, where less P was extracted from large aggregates (> 0.5 mm) than from small aggregates (< 0.5 mm), and they explained this result as a composition difference rather than a physical difference among the aggregates.

For a given aggregate size, grinding and vigorous shaking of the soil sample in the extractant tended to increase Mehlich-1 extractable P; however, the increase

Table 6 Effect of aggregate sizes and P rates on Mehlich-1 extracted P of the soils (mg kg^{-1} soil) in the pot experiment

	Before planting		After no plants		After corn		After rice	
Treatment	Low-P	High-P	Low-P	High-P	Low-P	High-P	Low-P	High-P
Aggregate size (mm)								
Whole soil	5.97 a	33.19 c	4.14 ab	23.05 c	2.75 bc	13.71 c	3.38 ab	18.02 d
4.8	5.52 a	31.28 d	3.33 b	20.50 d	2.22 c	11.96 d	2.72 b	16.26 e
1.5	6.01 a	34.17 c	4.15 ab	23.48 c	2.68 bc	14.20 c	3.18 ab	19.84 c
0.35	6.38 a	36.54 b	4.65 a	26.95 b	3.39 ab	18.15 b	3.65 a	22.82 b
0.106	6.81 a	44.03 a	5.15 a	34.46 a	3.73 a	24.98 a	4.01 a	28.77 a
P rate (kg ha^{-1})								
0	2.76 C	28.73 D	2.32 C	22.44 C	1.93 C	13.78 D	1.86 C	17.83 D
20	4.03 C	30.90 C	2.90 C	23.19 C	2.42 C	15.35 C	2.45 C	19.04 C
60	6.38 B	35.98 B	4.34 B	25.50 B	3.25 B	17.22 B	3.64 B	22.37 B
120	11.41 A	47.76 A	7.59 A	30.42 A	4.35 A	20.05 A	5.60 A	26.14 A

Means followed by the same small letters or the same capital letters within columns are not significantly different at $P < 0.05$ using a least significant difference (LSD) test.

was small and significant only in the high-P soil (Table 2). It appears that grinding and vigorous shaking increased the accessibility of extractant to occluded P inside the aggregates of the high-P soil, which has a recent history of high-P application. However, in the low-P soil (without P previously applied), occluded P might be negligible and, consequently, grinding and shaking do not significantly increase extractable P in this soil.

Effect of soil aggregation on the extractability of newly added P and PBC

Although extractable P was always markedly higher in small aggregates, there was only a small difference among the aggregate sizes in the rate of extracted P (Figs 1,2). Although PBC of the separated aggregate fractions after 15 days incubation with newly added P tended to be negatively correlated with aggregate size (Fig. 3), the correlation was not significant for either soil and grinding did not affect the trend of P extractability and PBC. The results suggest that the consistently higher extractable P in the smaller aggregate resulted from higher initial extractable P in these aggregates, and the effect of aggregate size on P extractability of newly added P was small. It was expected that the smaller aggregates with higher surface area would have higher P sorption, consequently, PBC should be positively correlated with aggregate size, and grinding of soil samples should decrease PBC because of an increase in the surface area for P sorption. Our results, however, did not show this. These findings were in contrast to findings that show that P sorption by aggregates separated from the same soil increased with decreasing aggregate size, and increased with increasing reactive mass because of greater surface area for P sorption in smaller aggregates (Linquist *et al.* 1997; Wang *et al.* 2001). Our results suggest that the surface area of the aggregates did not significantly affect P extractability of newly added P. The different soil types probably contributed to differences in the behavior and properties of the soil aggregates and consequently, to difference in the P sorption ability of the aggregate size fractions. Widowati (2001) conducted research on the aggregate sizes of 19 soils that represented low-soluble P, and a wide range of mean weight diameter (MWD), clay, organic matter and exchangeable Al of 60 highly weathered soils collected from different upland areas in South-East Asia. The results showed that when aggregates were separated and then P was added, the Mehlich-1 extractable P after 2 weeks incubation of the smaller aggregates (< 0.212 mm) in most of the soils (12 of 19 soils) was significantly higher than that of the larger aggregates (2–4 mm) and, consequently, the PBC was negatively correlated with the aggregate size of these soils. Our findings in this study suggest that in Siniloan soil, soil aggregation had little effect on P extractability of newly added P and PBC. In high-P soil, the current soil test procedures, which require grinding and vigorous shaking of the soil sample, might overestimate the available P status of the soil because some, if not all, of the P located inside the aggregates may not be available for the plant.

Plant growth response to aggregate size at varying levels of P supply

The growth of both corn and rice was healthy throughout the pot experiments without any symptoms of nutrient deficiency, except for P. Greater plant growth and P uptake together with a lower R/S ratio of both corn and rice in the smaller aggregates indicated that there would be more available P in these aggregates. This was consistent with the higher Mehlich-1 extracted P that was found in the smaller aggregates in all cases (before planting, after no planting, after harvest of corn and rice) for both soils (Table 6). However, there was no interaction between P supply and aggregate size on the plant growth response in both rice and corn in low-P or high-P soils (Table 4); this was also indicated in Figs 4–7, for example, the shoot dry weight and P uptake response of plants to soil aggregate size was not influenced by P rates. This suggests that newly added P did not significantly influence the plant available P of different sized aggregates over the 5-week period. The higher plant available P in the smaller aggregates was likely to because of the initial difference in P status among aggregate fractions rather than the influence of soil aggregate size on P availability of newly added P. These pot experimental results were consistent with the laboratory results that newly added P had little influence on P extractability and PBC (Figs 1–3) after a short incubation. Furthermore, shoot growth and P uptake of rice in the smaller aggregate fractions were always markedly higher than in the larger aggregate fractions even when P supply was abundant (no further response of rice growth to P rates in high-P soil; Fig. 5). This evidence suggests that the affect of aggregate size on plant available P alone could not explain the greater plant growth in the smaller aggregate fraction. Although P uptake increased with decreasing aggregate size, no significant effect of aggregate size on P efficiencies could be found for either rice or corn (Table 3). The greater plant growth and total P uptake in small aggregates were always associated with greater root growth, especially root length (Table 5). In addition, the RL/RDW ratio was always higher in the smaller aggregate fraction for both rice and corn. Taken together, these results indicate that soil aggregate size had little influence on plant P availability of newly added P. The greater plant growth and P uptake found in the smaller aggregates can be attributed to greater root growth with longer and finer roots as a result of ensuring adequate soil aeration and increased soil–root contact for water and nutrient uptake, including P.

Increases in plant growth and total P uptake with decreasing aggregate size have also been reported in other studies (Cornforth 1968; Misra *et al.* 1988; Wiersum 1962). These researchers concluded that the lower P uptake in the beds of large aggregates compared with small aggregates was attributed to greater mechanical impedance to root penetration and lower availability of P in the large aggregates.

A problem that is often encountered in studies involving different-sized soil aggregates is the confounding of soil aeration effects with aggregate size. Small aggregates tend to pack more closely resulting in limited soil aeration for adequate root growth. Lack of aeration has been proposed to account for poor growth in seedbeds made up primarily of very small aggregates (Russell 1977). Poor aeration usually results in poor root growth and, therefore, reduces the ability of roots to uptake water and nutrients, including P; consequently resulting in poor plant growth. Aeration problems may be one of the main reasons leading to the many conflicting results of studies examining different-sized soil aggregates. In this study, flat clay pots eliminated the aeration problem and the soil in the pots was only approximately 4 cm high, thus, increasing exposure of the soil to the air. Furthermore, the pot was watered from the bottom by capillary rise to prevent aggregates from compacting and breaking. Therefore, we were able to investigate the true effect of natural soil aggregate size on plant P availability. This may also explain why the results reported here are not consistent with some earlier studies (Wang *et al.* 2001; Widowati 2001) that used a soil aggregate–vermiculite mixture (vermiculite growth system) to minimize the aeration problems of the smaller aggregates and the pots were watered from the top. These researchers found that plant growth and P uptake were lower in the smallest sized aggregates. One possible reason for this was that in vermiculite growth systems, soil compacting and aeration problems still occur with small aggregates, resulting in poor plant growth and nutrient uptake, including P, in these aggregates compared with the larger aggregates.

The findings in this study suggest that in Siniloan soil (Typic Palehumults), over a short time period, soil aggregation had little effect on short-term P extractability and plant P availability from recently applied P. However, it is not clear whether this effect will be the same for longer periods. Further works would be necessary to assess the influence of soil aggregation on long-term plant P availability. Furthermore, in determining the available P status of high-P soil, shaking and grinding of soil samples to less than 2 mm in preparation for P extraction as required in current soil P tests may lower the estimated P requirements by overestimating the available P status of the soil by increasing the accessibility of the extractant to P occluded inside the aggregates. This P may not be available to the plant.

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