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https://doi.org/10.5109/10092

出版情報：九州大学大学院農学研究院紀要. 53 (1), pp.193-200, 2008-02-28. Faculty of Agriculture, Kyushu University
バージョン：
権利関係：

J. Fac. Agr., Kyushu Univ., **53** (1), 193–200 (2008)

Evaluation of Phosphorus Status of Some Upland Soils in Myanmar

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(*Received November 9, 2007 and accepted November 30, 2007*)

In order to evaluate the phosphorus status of upland soils in Myanmar, 26 upland and 8 lowland soil samples were collected form surface (0~15 cm deep) and subsurface (15~30 cm deep) layers at 17 different places on different parent materials in eastern, central and lower parts of Myanmar. Concentrations of total, available, organic, and inorganic P were considerably varied with soils with ranges of 132 to 1414, 1 to 135, 37 to 265, and 89 to1167 mg P/kg, respectively. The concentrations were higher for the soils applied with P fertilizer in all of the four P parameters. In most soils, the available, organic and inorganic P concentrations depended on the concentration of total P.

In the sequential fractionation, inorganic P was separated into soluble and loosely–bound P, Al–P, Fe–P, occluded P, and Ca–P in the slightly acid to neutral soils and into Ca_2–P, Ca_8–P, Al–P, Fe–P, occluded P, and Ca_{10}–P in the neutral to slightly alkaline soils. In the former soils, the available P concentration was correlated with the concentrations of soluble and loosely–bound P, Al–P and Ca–P at the 1% significant level, and those pools were estimated as the main source for available P. In the latter soils, although Ca_2–P, Ca_8–P and Al–P were the predominant forms, the total P concentration was highly correlated with the concentrations of all forms of inorganic P, and total P was consequently considered to contribute to increase of plant–available P.

Suitable crop selection or appropriate soil and fertilizer management practice was suggested depending on the phosphorus status of soils.

INTRODUCTION

Myanmar is an agro–based country with arable land (95,560 km^2) occupying 14.1% of the national land (676,580 km^2) under the tropical to subtropical monsoon climate. The whole year is separated into following three seasons: hot (middle February to middle May), rainy (middle May to middle October), and dry–cold (middle October to middle February). Myanmar spreads from north to south, located between 92° 09' to 101° 10' E and 9° 58' to 28° 31' N, and has different natural conditions. The western, northern and eastern parts of the country are hilly regions varying from 915 to 2,134 m (Ministry of Agriculture and Irrigation, 2000), leaving plains in the central and southern parts.

In Myanmar, upland agriculture is mostly done under the rain–fed condition with excessive, insufficient or no application of chemical fertilizers (Egashira and Than, 2006). In tropical and subtropical regions, generally, phosphorus (P) deficiency of soil is often a factor limiting crop production. However, sufficient application of P fertilizer is not easy for the resource–poor farmers. Insufficient P status of soil can result in the delayed crop maturity, reduced flower development, low seed quality, and depressed crop yield. Growing of mining crops such as cotton, maize, etc. on the nutrient–deficient soils can produce soils exhausted in P. On the other hand, large P application may cause eutrophication (Hyland *et al.*, 2005) of surrounding water systems. The P status of upland soils in Myanmar is not well examined yet.

The objective of the present study was to evaluate the P status of upland soils in Myanmar with reference to lowland soils. Based on the evaluation of P status and clarification of the factors controlling P availability of upland soils, selection of appropriate crops or cropping pattern and the proper fertility management were discussed to sustain crop production.

MATERIALS AND METHODS

Soils

Since Myanmar has different natural conditions such as topography, rainfall, temperature, parent materials, etc., soil characteristics probably differ with locations. Therefore, 26 upland soil samples and 8 lowland soil samples were collected from surface (0~15 cm deep) and subsurface (15~30 cm deep) layers at 17 places having different fertilization histories on different parent materials in eastern, central and lower parts of Myanmar in March 2006 (Fig. 1, and Tables 1 and 2). The bulk soil samples collected from each place were air–dried, ground and passed through a 2–mm sieve in the Soil Chemistry Department of the Central Agricultural Research Institute located in Yezin, Myanmar. Physical and chemical analyses, assessment of parameters representing P status, and sequential fractionation of inorganic P of soils were carried out in the Laboratory of Soil Science, Faculty of Agriculture, Kyushu University, Japan.

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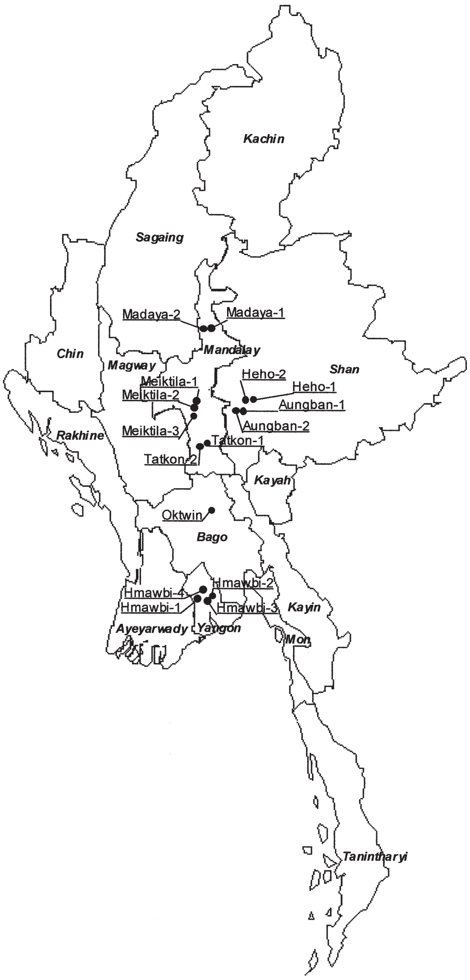

Fig. 1. Description of sampling sites on the administrative map of Myanmar.

Soil Analyses

Soil pH was measured by a pH meter in the suspension having a soil:water ratio of 1:2.5. The clay content was measured by the particle–size analysis in which the whole of each fraction was separated after complete dispersion and deflocculation of soils (Nguyen *et al.*, 2006). Exchangeable Ca was extracted with 1 M NH_4CH_3COO at pH 7 followed by determination with an atomic spectrophotometer.

Assessment of P parameters of soils

Total P was measured by the Na_2CO_3 fusion method, and available P was by extraction with the $NaHCO_3$ solution. Organic P was measured by the ignition method, and inorganic P was obtained by subtracting organic P from total P. All methods were referred to Olsen and Sommers (1982).

Sequential fractionation of inorganic P

Since plants absorb P in a form of inorganic ion from soil solution, fractionation of inorganic P was approached to evaluate which fraction contributes to available P. According to the wide variation of soil pH from 5.06 to 8.92 (Table 3), fractionation was applied separately to calcareous and noncalcareous soils. Since the pH of Tatkon–1 and Tatkon–2 was around 7.5 naturally, while the pH of Hmawbi–2 was about 7.4 due to liming, they were subjected to the fractionation in both categories.

The samples of slightly acid to neutral soils were subjected to the fractionation scheme described by Kuo (1996a, b) to noncalcareous soils. Inorganic P was divided into five fractions of (1) soluble and loosely–bound P, (2) Al–P, (3) Fe–P, (4) occluded P, and (5) Ca–P which

Table 1. General information of soil samples

No	Location and sample name	State/Division	Topography	Parent material	Soil classification[1)]	Rainfall[2)] (mm/y)
1	Heho–1	Southern Shan State	Hill	Limestone	Red earth and yellow earth (Acrisoils)	1022
2	Heho–2	Southern Shan State	Hill	Limestone	Red earth and yellow earth (Acrisols)	1022
3	Aungban–1	Southern Shan State	Hill	Limestone	Red earth and yellow earth (Acrisols)	1022
4	Aungban–2	Southern Shan State	Hill	Limestone	Red earth and yellow earth (Acrisols)	1022
5	Madaya–1	Mandalay Division	Meander floodplain	Alluvium	Dark compact soils (Vertisols)	855
6	Madaya–2	Mandalay Division	Meander floodplain	Alluvium	Light forest soils (Nitosols)	855
7	Meiktila–1	Mandalay Division	Inland valley	Limestone sediment	Yellow–brown dry forest and indaing soils (Orthic Cambisols)	866
8	Meiktila–2	Mandalay Division	Inland valley	Limestone sediment	Yellow–brown dry forest and indaing soils (Orthic Cambisols)	866
9	Meiktila–3	Mandalay Division	Inland valley	Limestone sediment	Yellow–brown dry forest and indaing soils (Orthic Cambisols)	866
10	Tatkon–1	Mandalay Division	Inland valley	Limestone sediment	Light forest soils (Nitosols)	1028
11	Tatkon–2	Mandalay Division	Inland valley	Limestone sediment	Light forest soils (Nitosols)	1028
12	Tatkon–3	Mandalay Division	Inland valley	Limestone sediment	Light forest soils (Nitosols)	1028
13	Oktwin	Bago Division	Meander floodplain	Alluvium and limestone sediment	Meadow alluvial soils(Fluvic Gleysols)	3320
14	Hmawbi–1	Yangon Division	Deltaic plain	Alluvium	Meadow alluvial soils (Fluvic Gleysols)	2757
15	Hmawbi–2	Yangon Division	Deltaic plain	Old alluvium	Latritic soils (Plinthic Ferrasols)	2757
16	Hmawbi–3	Yangon Division	Deltaic plain	Old alluvium	Latritic soils (Plinthic Ferrasols)	2757
17	Hmawbi–4	Yangon Division	Deltaic plain	Old alluvium and limestone sediment	Yellow–brown forest soils (Xanthic Ferralsols)	2757

[1)] Soil classification estimated based on the book 'Soil Types and Characteristics of Myanmar' published by the Ministry of Agriculture and Irrigation (2004), and the equivalent soil name by the FAO/UNESCO system is described in the parenthesis.
[2)] Records of the Meteorological Stations and Rainfall Stations of the Department of Meteorology and Hydrology.

Table 2. Cropping system, fertilizer usage and crop performance of the sampled soils

No	Sample name	Cropping system	Fertilizer usage (kg/ha/y)					Crop performance
			Urea	TSP	Potash	FYM	Others	
1	Heho–1	Rainy season (R): maize	50	50	100		Ca, Zn, S (trace)	Fair
		Winter season (W): wheat or chickpea						
2	Heho–2	R: paddy rice	100	50		–	Ca, Zn, S (100)	Fair
		W: garlic or cabbage	300	200	150			
		Summer season (S): potato	100	200	100	2500 (cowdang)		
3	Aungban–1	R: upland rice	100	–	–	500 (cowdang)		Moderately poor
		W: taro						
4	Aungban–2	R: maize	100	–	–	–	100 (compound)	Moderately poor
		W: wheat					100 (compound)	
5	Madaya–1	R: paddy rice	100	–	–	–		Fair
		S: paddy rice	100	–	–	500 (cowdang)		
6	Madaya–2	Sunflower or fallow	–	–	–	—	–	Fair
7	Meiktila–1	R: greengram–sesame intercropping	–	–	–	1000 (cowdang)		Poor
		W: cotton–sunflower intercropping						
8	Meiktila–2	Sunflower	–	–	–			Poor
9	Meiktila–3	R: cotton; W: chickpea	–	–	–			Poor
	(Maize and cotton cultivation in Tatkon–1, –2, –3 during 15 y)		250	250	125			
10	Tatkon–1	R: greengram	50	50				Fair
		W: chickpea						Fair
11	Tatkon–2	R: greengram; W:chickpea					Folier (com-	Moderately poor
12	Tatkon–3	R: maize	100	100	50	Compost of cowdang	pound)	Good
		W: sunflower, lab–lab bean	50	50	25	and crop residues		
13	Oktwin	R: paddy rice						Fair
		W: blackgram	50					Fair
14	Hmawbi–1	R: paddy rice						Fair
		S: paddy rice						
15	Hmawbi–2	Vegetables (pepper, cucumber, etc.) in greenhouse	Intensive fertilizer use weekly and in every crop season			Peanut cake, chicken and cowdang manure	CaO	Excellent
16	Hmawbi–3	Outside the greenhouse and broadcasted with P fertilizer before it was built						
17	Hmawbi–4	Border area of orchard						

were sequentially extracted with (1) 1 M NH_4Cl, (2) 0.5 M NH_4F, (3) 0.1 M NaOH, (4) 0.3 M $Na_2C_3H_6O_7$–$Na_2S_2O_4$–1 M $NaHCO_3$, and (5) 0.25 M H_2SO_4, respectively.

For the samples of neutral to slightly alkaline soils, fractionation was done by the method conducted to calcareous soils by Jiang and Gu (1989), and inorganic P was divided into six fractions of (1) Ca_2–P, (2) Ca_8–P, (3) Al–P, (4) Fe–P, (5) occluded P, and (6) Ca_{10}–P. Each fraction was roughly corresponding to the following pools: Ca_2–P represents monocalcium phosphate [$Ca(H_2PO_4)_2$] and dicalcium phosphate [$CaHPO_4 \cdot nH_2O$] equivalents and includes water–soluble P, citrate–soluble P and partial surface–adsorbed P which can be readily taken up by plants; Ca_8–P represents a group of phosphates having a chemical composition similar to $Ca_8H_2(PO_4)_6 \cdot nH_2O$ and belongs to the sparingly soluble P which can be constrainedly utilized by plants when soil was severely depleted of available P; Ca_{10}–P represents a group of phosphates with a chemical composition similar to $Ca_{10}(PO_4)_6(OH)_2$ which is difficult to be used by plants (Gu and Jiang, 1990; Shen *et al.*, 2004).

In the method by Jiang and Gu (1989), soil sample was successively extracted with (1) 0.25 M $NaHCO_3$, (2) 0.5 M NH_4CH_3COO, (3) 0.5 M NH_4F, (4) 0.1 M NaOH–0.1 M Na_2CO_3, (5) 0.3 M $Na_3C_6H_5O_7$–$Na_2S_2O_4$–0.5 M NaOH, and (6) 0.25 M H_2SO_4. In the citrate–dithionite extraction, hot water bathing for 15 min at 85 °C was modified to 16–hr shaking (Ruiz *et al.*, 1997). To eliminate interference with some ions or compounds, the NH_4F extract was treated with boric acid, and the citrate–dithionite extract was digested with a mixture of three acids (1 part of $HClO_4$, 2 parts of H_2SO_4 and 7 parts of HNO_3). After each extraction, the sample was washed with ethanol in the 1st step and with 1 M $MgCl_2$ in the 2nd through 5th steps to determine the amount of readsorbed P (Adhami *et al.*, 2006).

Concentrations of all forms of P were measured by the ascorbic acid method (Murphy and Riley, 1962). Correlation between P parameters was analyzed statistically by the Stat View correlation matrix.

RESULTS AND DISCUSSIONS

Physical and chemical properties of soils

Selected physical and chemical properties of surface and subsurface layers of soils are shown in Table 3. The pH of the soils was in a range from 5.06 to 8.92 and was over 8.0 in Heho–2, and Meiktila–1 through Meikitila–3. The high content of exchangeable Ca was found in Heho–2; it is probably due to deposition of Ca–containing rock or sediment from the surrounding mountain to the foot.

Total, available, organic, and inorganic P status

Concentrations of total, available, organic, and inorganic P of surface and subsurface layers of soils, shown in Table 3, ranged from 132 to 1414, 1 to 135, 37 to 265, and 89 to 1167 mg P/kg, respectively. Among the unfertilized soils, the extremely low level of total and available

Table 3. The pH, clay percentage, exchangeable Ca content, and concentrations of total, available, organic, and inorganic P in mg P/kg of soils from 0–15 and 15–30 cm depths

No	Sample name	Depth (cm)	pH	Clay (<2 μm) (%)	Exchangeable Ca ($cmol_c$/kg)	Total P	Available P	Organic P	Inorganic P
1	Heho–1	0–15	6.80	42.6	3.2	722	14 (2)	249 (34)	473 (66)
2		15–30	6.53		2.9	680	12 (2)	265 (39)	415 (61)
3	Heho–2	0–15	8.43	17.6	36.8	655	33 (5)	247 (38)	408 (62)
4		15–30	8.10		34.5	589	38 (6)	215 (37)	374 (63)
5	Aungban–1	0–15	5.69	27.1	1.9	329	4 (1)	142 (43)	187 (57)
6		15–30	5.94		1.4	258	3 (1)	129 (50)	129 (50)
7	Aungban–2	0–15	6.49			332	4 (1)	162 (49)	170 (51)
8		15–30	5.06			267	3 (1)	130 (49)	137 (51)
9	Madaya–1	0–15	7.12	49.9	10.5	323	9 (3)	112 (35)	211 (65)
10		15–30	7.92		11.3	359	10 (3)	101 (28)	258 (72)
11	Madaya–2	0–15	7.73	29.1	6.2	565	20 (4)	118 (21)	447 (79)
12		15–30	8.07		7.3	558	12 (2)	85 (15)	473 (85)
13	Meiktila–1	0–15	8.89	9.7	8.8	133	8 (6)	37 (28)	96 (72)
14		15–30	8.92		24.8	133	1 (1)	39 (29)	94 (71)
15	Meiktila–2	0–15	8.18			140	8 (6)	51 (36)	89 (64)
16		15–30	8.01			192	4 (2)	60 (31)	132 (69)
17	Meiktila–3	0–15	8.64	43.7	11.6	147	2 (1)	48 (33)	99 (67)
18		15–30	8.83		14.5	132	1 (1)	39 (30)	93 (70)
19	Tatkon–1	0–15	7.58	28.3	7.1	414	15 (4)	135 (33)	279 (67)
20		15–30	7.54		6.5	372	10 (3)	136 (37)	236 (63)
21	Tatkon–2	0–15	7.64			354	9 (3)	121 (34)	233 (66)
22		15–30	7.75			352	7 (2)	112 (32)	240 (68)
23	Tatkon–3	0–15	6.95	5.9	2.2	397	37 (9)	77 (19)	320 (81)
24		15–30	7.18		2.0	407	34 (8)	77 (19)	330 (81)
25	Oktwin	0–15	5.28	16.7	1.8	272	9 (3)	78 (29)	194 (71)
26		15–30	6.51		2.6	248	4 (2)	73 (29)	175 (71)
27	Hmawbi–1	0–15	5.66	23.3	1.9	279	8 (3)		
28		15–30	6.65		2.3	235	6 (3)		
29	Hmawbi–2	0–15	7.42	21.3	12.7	1414	135 (10)	247 (17)	1167 (83)
30		15–30	7.12		5.7	548	74 (14)	178 (32)	370 (68)
31	Hmawbi–3	0–15	6.05	25.5	2.5	363	50 (36)		
32		15–30	5.15		0.9	213	7 (3)		
33	Hmawbi–4	0–15	6.63	10.3	1.6	364	7 (2)	86 (24)	278 (76)
34		15–30	6.85		1.2	343	7 (2)	81 (24)	262 (76)

Values in the parenthesis are the percentage to the total P concentration.

P was found in the soils (Orthic Cambisols) from Meiktila region in the central part of Myanmar, derived from limestone sediment. The total and available P concentrations were both under the critical levels of 175 mg P/kg as total P for paddy soils (Kawaguchi and Kyuma, 1977) and of 10 mg P/kg as available Olsen P for upland crops (Olsen and Sommers, 1982).

Soils from other regions were in the medium P level. However, the available P concentration of most unfertilized soils was under the critical level of 10 mg P/kg as available Olsen P (Olsen and Sommers, 1982). In the same region, lowland soils were in the lower P level than upland soils, although regional difference in the P status was larger than the difference due to land use. Phosphorus fertilization severely affected the P status of soil, and soils which have been supplied with P fertilizer, such as Hmawbi–2, Heho–1, Heho–2, and Tatkon–3, were higher in the concentrations of all four P parameters.

Considerable difference in the total and available P concentrations was noticed among the samples colleted in Hmawbi region. In this context, Hmawbi–1 and Hmawbi–3 were not measured in organic P, and organic and inorganic P concentrations of them were not involved in Table 3. Hmawbi–1 and Hmawbi–4 were below the critical level of available P in both surface and subsurface layers. It indicates the generally insufficient P level of soils in Hmawbi region. Different from Hmawbi–1 and Hmawbi–4, Hmawbi–2 which is under excessive application of lime, triple super phosphate and poultry manure (Table 2) showed the extraordinarily high concentrations of total and available P, especially in the surface layer. Hmawbi–3 was taken from just outside the Hmawbi–2 vegetable greenhouse (Table 2), and the total and available P concentrations were remarkably different between surface and subsurface layers.

If we exclude Hmawbi–2, ranges in the concentrations of total and available P were similar to those of Bangladesh paddy soils (Egashira *et al.*, 2003). In comparison with total P of Lao paddy soils from the central region of Mekong River (Egashira *et al.*, 1996), the lower limit of Myanmar soils in the present study was lower than that of the Lao paddy soils. In addition, the upper limit of total P concentration in the Lao paddy soils was similar to the value of Hmawbi–2.

Correlation coefficients between four P parameters were calculated except Hmawbi–1 and Hmawbi–3 and are shown in Table 4. However, the correlation between

Table 4. Correlation coefficients between concentrations of total P, available P, organic P, and inorganic P of soils except Hmawbi–1 and Hmawbi–3

	Available P	Organic P	Inorganic P
Total P	0.826**	0.783**	0.979**
Available P		0.500**	0.857**
Organic P			0.641**

Number of observations is 30. ***P*<0.01.

Table 5. Correlation coefficients between concentrations of total P, available P, organic P, and inorganic P of soils except Hmawbi–1, Hmawbi–2 and Hmawbi–3

	Available P	Organic P	Inorganic P
Total P	0.609**	0.833**	0.957**
Available P		0.383*	0.649**
Organic P			0.636**

Number of observations is 28.
**P*<0.05. ** *P*<0.01.

any combinations of four P parameters was significant at the 1% level. Since Hmawbi–2 under excessive application of P fertilizer, as already described, had extremely high levels of all P parameters, Hmawbi–2 was excluded in addition to Hmawbi–1 and Hmawbi–3 in the calculation of correlation coefficients, and the result is given in Table 5.

As shown in Table 5, total P was highly correlated with available P (r=0.609**), organic P (r=0.833**), and inorganic P (r=0.957**) at the 1% level. It was found that the concentrations of available P, organic P and inorganic P depended significantly on the concentration of total P. Meanwhile, available P was significantly correlated with total P (r=0.609**) and inorganic P (r=0.649**) at the 1% level but with organic P (r=0.383*) at the 5% level. Therefore, it was considered that available P was more closely related with total P and inorganic P than with organic P.

Fractionation of inorganic P

Slightly acid to neutral soils

Table 6 shows the data on the fractionation of slightly acid to neutral soils having the pH range of 5.06 to 7.75. In Table 6, inorganic P (S) in column 7 is the concentration which was obtained by subtracting the organic P concentration from the total P concentration and the same as the values in column 10 of Table 3. On the other hand, fractions' total (F) in column 13 is the total of the concentrations of all inorganic P fractions. Difference D1 in column 14 is the difference between inorganic P (S) and fractions' total (F) and probably happens due to the weakness of analytical procedures for the organic P measurement and/or the inorganic P fractionation; it was generally smaller than difference D2 in Table 8 for the neutral to slightly alkaline soils.

As for the parameters representing the P status of slightly acid to neutral soils, the extraordinarily high P level was found to Hmawbi–2 (1,414 mg P/kg of total P and 135 mg P/kg of available P in the surface layer) collected from the vegetable green house under intensive

Table 6. The pH, and concentrations (mg/kg) of total P, available P, inorganic P (S), and total and fractionated inorganic P of slightly acid to neutral soils

No	Sample name	Depth (cm)	pH	Total P	Available P	Inorganic P (S)	Inorganic P fractions: Soluble and loosely–bound P	Al–P	Fe–P	Occluded P	Ca–P	Fractions' total (F)	Difference D1 (S–F)
1	Heho–1	0–15	6.80	722	14	473	0.7 (0.1)	49 (11)	167 (37)	179 (40)	54 (12)	450	23
2		15–30	6.53	680	12	415	0.3 (0.1)	41 (10)	154 (36)	177 (42)	50 (12)	423	–8
3	Aungban–1	0–15	5.69	329	4	187	0.5 (0.3)	10 (7)	52 (34)	76 (50)	12 (8)	151	36
4		15–30	5.94	258	3	129	0.0 (0.0)	5 (4)	31 (26)	71 (60)	12 (10)	119	10
5	Aungban–2	0–15	6.49	332	4	170	0.7 (0.4)	7 (4)	55 (34)	87 (54)	13 (8)	162	8
6		15–30	5.06	267	3	137	0.3 (0.3)	4 (4)	29 (31)	52 (55)	10 (11)	95	42
7	Tatkon–1	0–15	7.58	414	15	279	2.4 (0.8)	26 (9)	74 (26)	136 (48)	43 (15)	282	–3
8		15–30	7.54	372	10	236	1.4 (0.5)	15 (6)	60 (24)	136 (55)	35 (14)	247	–11
9	Tatkon–2	0–15	7.64	354	9	233	1.4 (0.6)	15 (6)	56 (24)	117 (51)	41 (18)	231	2
10		15–30	7.75	352	7	240	0.7 (0.3)	13 (5)	53 (22)	125 (53)	46 (19)	237	3
11	Tatkon–3	0–15	6.95	397	37	320	20.9 (6.6)	59 (19)	89 (28)	67 (21)	81 (25)	318	2
12		15–30	7.18	407	34	330	20.9 (6.6)	55 (17)	92 (29)	68 (21)	81 (26)	317	13
13	Oktwin	0–15	5.28	272	9	194	0.7 (0.4)	5 (3)	67 (41)	75 (46)	14 (9)	162	32
14		15–30	6.51	248	4	175	0.7 (0.4)	3 (2)	56 (34)	88 (53)	18 (11)	166	9
15	Hmawbi–1	0–15	5.66	279	8		0.7 (0.4)	5 (3)	80 (48)	75 (45)	5 (3)	166	
16		15–30	6.65	235	6		0.3 (0.3)	5 (4)	53 (41)	65 (50)	6 (5)	130	
17	Hmawbi–2	0–15	7.42	1414	135	1167	195.7 (13.5)	484 (33)	175 (12)	442 (30)	157 (11)	1455	–288
18		15–30	7.12	548	74	370	13.8 (3.4)	255 (62)	73 (18)	46 (11)	21 (5)	409	–39
19	Hmawbi–3	0–15	6.05	363	50		11.5 (3.7)	175 (57)	62 (20)	48 (16)	13 (4)	308	
20		15–30	5.15	213	7		0.7 (0.8)	20 (24)	27 (33)	26 (32)	7 (9)	82	
21	Hmawbi–4	0–15	6.63	364	7	278	9.1 (4.0)	56 (25)	90 (39)	60 (26)	13 (6)	228	50
22		15–30	6.85	343	7	262	5.4 (2.7)	46 (23)	86 (43)	54 (27)	7 (4)	199	63

Values in the parenthesis are the percentage to the fractions' total P concentration.

cropping with excessive P fertilization (Table 2). The sufficient P level (372 to 722 mg P/kg of total P and 10 to 37 mg P/kg of available P in both surface and subsurface layers) was found to well–fertilized soils of Heho–1, Tatkon–1 and Tatkon–3. The insufficient P level (248 to 364 mg P/kg of total P and 3 to 9 mg P/kg of available P in both surface and subsurface layers) was found to Aungban–1, Aungban–2, Tatkon–2, Oktwin and Hmawbi–4 with insufficient or no application of P fertilizer. Soils in the insufficient P level exceeded the critical level in total P but were below the critical level in available P.

As shown in Table 6, concentrations of the respective inorganic P fractions of slightly acid to neutral soils were as follows:

Soluble and loosely–bound P: 0.0 to 195.7 mg P/kg with 0.0 to 13.5% of fractions' total;

Al–P: 3 to 484 mg P/kg with 2 to 62% of fractions' total;

Fe–P: 27 to 175mg P/kg with 12 to 48% of fractions' total;

Occluded P: 26 to 442 mg P/kg with 11 to 60% of fractions' total;

Ca–P: 5 to 157 mg P/kg with 3 to 26% of fractions' total.

As usual, Al–P, Fe–P and occluded P were found to be the dominant inorganic P fractions in slightly acid to neutral soils.

Table 7 lists correlation coefficients between concentrations of total P, available P, inorganic P (S), and total and fractionated inorganic P of slightly acid to neutral soils. In the calculation, organic P was not included, and Hmawbi–1, Hmawbi–2 and Hmawbi–3 were excluded with sample number of 16. Total P was highly correlated with inorganic P (S) (r=0.932**), Fe–P (r=0.933**), occluded P (r=0.780**), and IP fractions' total (F) (r=0.930**) at the 1% level, and with Al–P (r=0.582*) and Ca–P (r=0.532*) at the 5% level. Total P can be mentioned to be more significantly correlated with Fe–P and occluded P among the different forms of inorganic P.

Available P was correlated significantly with soluble and loosely–bound P (r=0.881**), Al–P (r=0.690**), and Ca–P (r=0.893**) at the 1% level, and with inorganic P (S) (r=0.548*) and IP fractions' total (F) (r=0.579*) at the 5% level, but insignificantly with total P (r=0.320), Fe–P (r=0.392), and occluded P (r=0.012). Therefore, it became evident that soluble and loosely–bound P, Ca–P and Al–P were the more important fractions for P availability in the slightly acid and neutral soils. Ca–P was a least soluble form, but it played a relatively important role as a pool of available P.

Although Fe–P and occluded P were dominant inorganic P fractions, they were not significantly correlated with available P. The concentrations of available P and all inorganic P fractions were higher in Heho–1, Tatkon–1, Tatkon–3 and Hmawbi–2 which have been subjected to P fertilization. However, increase in Fe–P and occluded P by fertilization with P did not enhance the concentration of available P. It seemed to be due to fixation of P compounds by different forms of iron under the slightly acid to neutral condition. In this context, appropriate application of P fertilizer to prevent from fixation by iron oxides/hydroxides is necessary.

Neutral to slightly alkaline soils

Table 8 shows the data on the fractionation of neutral to slightly alkaline soils having the pH range of 7.12 to 8.92. Tatkon–1, Tatkon–2 and Hmawbi–2 are included in both Tables 6 and 8. Inorganic P (S) of column 7, fractions' total (F) of column 15 and difference D2 of column 16 are the same as those described in Table 6. After each extraction, following Adhami *et al.* (2006) who studied inorganic P fractionation of highly calcareous soils of Iran, the sample was washed with ethanol in the 1st step and with 1 M $MgCl_2$ in the 2nd through 5th steps in the sequential fractionation to determine the amount of readsobed P. However, appreciable quantity of readsobed P was detected only in the 2nd–step washing, similar to Adhami *et al.* (2006), and shown in the column following the column of Ca_8–P in Table 8.

Concerning the parameters representing the P status in neutral to slightly alkaline soils, the P level of the samples could be divided into four groups. It was extraordinarily high P level to Hmawbi–2, sufficient P level to Heho–2, Madaya–2 and Tatkon–1, insufficient P level to Madaya–1 and Tatkon–2, and poor P level to Meiktila–1 through Meiktila–3. In the slightly acid to neutral soils, the poor P level was not identified (Table 6). Soils from Meiktila region were severely lower than the critical levels in both total and available P, and supply of sufficient P with appropriate soil management is urgently necessary.

Table 7. Correlation coefficients between concentrations of total P, available P, inorganic P (S), and total and fractionated inorganic P of slightly acid to neutral soils except Hmawbi–1, Hmawbi–2 and Hmawbi–3

	Available P	Inorganic P (S)	Soluble and loosely–bound P	Al–P	Fe–P	Occluded P	Ca–P	IP fractions' total (F)
Total P	0.320	0.932**	0.093	0.582*	0.933**	0.780**	0.532*	0.930**
Available P		0.548*	0.881**	0.690**	0.392	0.012	0.893**	0.579*
Inorganic P (S)			0.325	0.789**	0.958**	0.630**	0.680**	0.977**
Soluble and loosely–bound P				0.728**	0.192	–0.378	0.655**	0.301
Al–P					0.720**	0.075	0.594*	0.711**
Fe–P						0.607*	0.493	0.915**
Occluded P							0.380	0.723**
Ca–P								0.758**

Number of observations is 16. * $P<0.05$. ** $P<0.01$.

Table 8. The pH, and concentrations (mg/kg) of total P, available P, inorganic P (S), and total and fractionated inorganic P of neutral to slightly alkaline soils

No	Sample name	Depth (cm)	pH	Total P	Avail–able P	Inorgan–ic P (S)	Inorganic P fractions								Difference D2 (S–F)
							Ca_2–P	Ca_8–P	Readsorbed P	Al–P	Fe–P	Occluded P	Ca_{10}–P	Fractions' total (F)	
1	Heho–2	0–15	8.43	655	33	408	23 (6)	14 (14)	7 (2)	47 (12)	15 (4)	115 (30)	157 (42)	378	30
2		15–30	8.10	589	38	374	16 (5)	11 (3)	4 (1)	36 (11)	9 (3)	111 (34)	143 (43)	330	44
3	Madaya–1	0–15	7.12	323	9	211	5 (4)	5 (4)	1 (1)	6 (5)	8 (6)	61 (46)	46 (35)	132	79
4		15–30	7.92	359	10	258	8 (4)	7 (4)	1 (1)	10 (6)	11 (6)	81 (45)	62 (34)	179	79
5	Madaya–2	0–15	7.73	565	20	447	18 (5)	145 (41)	33 (9)	27 (8)	13 (4)	65 (19)	49 (14)	350	97
6		15–30	8.07	558	12	473	12 (3)	174 (47)	33 (9)	28 (8)	19 (5)	59 (16)	42 (11)	367	106
7	Meiktila–1	0–15	8.89	133	8	96	1 (2)	12 (24)	4 (8)	4 (8)	3 (6)	9 (18)	16 (33)	49	47
8		15–30	8.92	133	1	94	1 (3)	5 (13)	2 (5)	3 (8)	3 (8)	9 (23)	17 (43)	40	54
9	Meiktila–2	0–15	8.18	140	8	89	6 (7)	12 (13)	5 (5)	9 (10)	7 (8)	28 (31)	24 (26)	91	–2
10		15–30	8.01	192	4	132	3 (3)	6 (7)	1 (1)	4 (5)	8 (9)	40 (46)	25 (29)	87	45
11	Meiktila–3	0–15	8.64	147	2	99	2 (5)	4 (9)	1 (2)	4 (9)	3 (7)	13 (30)	17 (39)	44	55
12		15–30	8.83	132	1	93	1 (4)	3 (11)	1 (4)	2 (7)	2 (7)	7 (25)	12 (43)	28	65
13	Tatkon–1	0–15	7.58	414	15	279	14 (5)	15 (6)	4 (1)	18 (7)	24 (9)	139 (51)	58 (21)	272	7
14		15–30	7.54	372	10	236	7 (3)	8 (4)	2 (1)	10 (5)	10 (5)	113 (51)	70 (32)	220	16
15	Tatkon–2	0–15	7.64	354	9	234	8 (4)	10 (5)	2 (1)	11 (6)	20 (10)	101 (51)	47 (24)	199	35
16		15–30	7.75	352	7	240	7 (3)	9 (4)	2 (1)	11 (5)	14 (7)	111 (53)	54 (26)	207	33
17	Hmawbi–2	0–15	7.42	1414	135	1167	185 (17)	297 (27)	160 (15)	215 (20)	78 (7)	63 (6)	102 (15)	1100	67
18		15–30	7.12	548	74	370	57 (3)	81 (18)	44 (10)	160 (35)	44 (10)	33 (7)	35 (8)	454	–84

Values in the parenthesis are the percentage to the fractions' total P concentration.

Table 9. Correlation coefficients between concentrations of total P, available P, inorganic P (S), and total and fractionated inorganic P of neutral to slightly alkaline soils except Heho–2, Madaya–1, Madaya–2 and Hmawbi–2

	Available P	Inorganic P (S)	Ca_2–P	Ca_8–P	Readsorbed P	Al–P	Fe–P	Occluded P	Ca_{10}–P	IP fractions' total (F)
Total P	0.762*	0.998**	0.860**	0.491	0.062	0.875**	0.879**	0.993**	0.958**	0.983**
Available P		0.755*	0.883**	0.906**	0.639*	0.908**	0.805**	0.794**	0.756*	0.843**
Inorganic P(S)			0.856**	0.495	0.056	0.873**	0.907**	0.990**	0.941**	0.997**
Ca_2–P				0.750*	0.428	0.991**	0.928**	0.894**	0.807**	0.924**
Ca_8–P					0.860**	0.776**	0.654*	0.543	0.473	0.613
Readsorbed P						0.468	0.248	0.134	0.117	0.225
Al–P							0.931**	0.909**	0.826**	0.938**
Fe–P								0.908**	0.778**	0.917**
Occluded P									0.962**	0.995**
Ca_{10}–P										0.959**

Number of observations is10. * $P<0.05$. ** $P<0.01$.

As shown in Table 8, concentrations of the respective inorganic P fractions of neutral to alkaline soils were as follows:

Ca_2–P: 1 to 185 mg P/kg with 2 to 17% of fractions' total;
Ca_8–P: 3 to 297 mg P/kg with 3 to 47% of fractions' total;
Al–P: 2 to 215 mg P/kg with 5 to 35% of fractions' total;
Fe–P: 2 to 78 mg P/kg with 3 to 10% of fractions' total;
Occluded P: 7 to 139 mg P/kg with 6 to 53% of fractions' total;
Ca_{10}–P: 12 to 157 mg P/kg with 8 to 43% of fractions' total.

Among the inorganic P fractions of neutral to slightly alkaline soils, occluded P, Ca_8–P and Ca_{10}–P were dominant forms in the soils with natural pH of higher than 7.7. However, Hmawbi–2 had high pH induced by liming, and its P status was extreamly high as mentioned above. Heho–2 and Madaya–1 were lowland soils. Madaya–2 differed from other neutral to slightly alkaline soils in the high value of Ca_8–P as the most predominant inorgnic P fraction. Therefore, correlation was made for the neutral to slightly alkaline soils excluding Heho–2, Madaya–1, Madaya–2 and Hmawbi–2. As a result, sample number was only 10, and correlation coefficients are listed in Table 9.

As shown in Table 9, reabsorbed P obtained in the 2nd–step washing after extraction of Ca_8–P was highly correlated with Ca_8–P with a correlation coefficient of r=0.860**, and hence these two components can be combined as Ca_8–P. Total P was significantly correlated with most of P parameters and IP fractions at the 1% level. Available P was also significantly correlated with Al–P (r=0.908**), Ca_8–P (r=0.906**), Ca_2–P (r=0.883**), Fe–P (r=0.805**) and occluded P (r=0.794**) at the 1% level, and with total P (r=0.762*) and Ca_{10}–P (r=0.756*) at the 5% level.

In Madaya–2 under the fallow condition, the Olsen P was sufficient and nearly the same level as the concentration of Ca_2–P. The Ca_8–P fraction as the predominant inorganic P fraction in Madaya–2 suggests that Ca_8–P (sparingly soluble form of octacalcium phosphate) remains as an adsorbed form more or less stably under the condition without being taken up by plants and no depletion of available P and Ca_2–P (readily available form of dicalcium phosphate). In Hmawbi–2 taken from the greenhouse established about 10 years ago, the remediation of soil acidity by liming and the heavy application of organic and inorganic P fertilizers made the total and available P status extremely high dominated with relatively soluble inorganic P fractions.

In the neutral to slightly alkaline soils, Ca_2–P, Ca_8–P and Al–P were most highly correlated with total and available P, but all other inorganic P fractions were also highly correlated with them at the 1 or 5% level. Therefore, it was considered that increase in total P would increase all of inorganic P forms and consequently contribute to increase of plant–available P.

SUMMARY AND CONCLUSIONS

Ranges of total, available, organic, and inorganic P concentrations of the soils in the present study were 132~1414, 1~135, 37~265, and 89~1167 mg P/kg, respectively. For most soils, the available, organic and inorganic P concentrations depended on the total P concentration. Soils which have been applied with P fertilizer were higher in all of four different parameters representing the P status. The extremely high concentrations of all P parameters were found to Hmawbi–2 subjected to excessive fertilizer application. Among the unfertilized soils, the lowest P level was found to soils from Meiktila and Aungban regions, and soils from other regions were in the medium P level.

In slightly acid to neutral soils, soluble and loosely–bound P, Ca–P and Al–P were dominant fractions to support P availability. Increase in Fe–P and occluded P by increasing total P did not enhance available P. It seemed to be due to fixation of P compounds by different forms of iron under the slightly acid to neutral condition. Appropriate application of P fertilizer to prevent from fixation by iron oxides/hydroxides is necessary for optimum crop production.

In neutral to slightly alkaline soils, all P parameters and inorganic P fractions were highly correlated with both total P and available P. It suggests that increase in total P would increase all of inorganic P forms and consequently contribute to increase of plant–available P. The P status of soils from Meiktila region was severely lower than the critical level in both total and available P. It was probably due to P fixation by iron oxides/hydroxides and apatite in these soils, because the P in these two fractions was highly correlated with total P but least with available P.

On the exhausted soils of total and available P under the critical level, like those in Meiktila region, beneficial crops such as legumes should be grown with sufficient supply of P fertilizer and proper soil management to keep high absorption rate of P, instead of cropping with mining crops. In soils with fertilization–induced excess P such as Hmawbi–2, application of P fertilizer should be reduced to save it for deficient soils and to conserve the environment.

ACKNOWLEDGEMENT

A part of soil properties was measured by Ms. Sayaka Hayashi as her graduate thesis in the Department of Bioresource and Bioenvironment, School of Agriculture, Kyushu University. We express our sincere thanks to her.

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