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REVIEW
Estimating Phosphorus Availability in Andosols Using Soil Biomass Phosphorus as an Indicator

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Abstract
Andosols are widely distributed in upland fields in Japan and are characterized by a high phosphorus (P) retention capacity. Consequently, the efficiency of P fertilizers is low in Andosols, requiring a high rate of P fertilizer application. However, P resources are becoming depleted globally, and excess P accumulated in soil inhibits trace element uptake by plants, pollutes the environment, and triggers outbreaks of soil-borne diseases. Available P in upland fields in Japan is usually estimated using the Truog method, but the results do not correlate with plant P uptake in Andosols. Soil organic P is also not usually evaluated as available, but remains an important P source for plants. The P in microbes (biomass P) is particularly important, because P from dead microbes is released directly into the soil or easily decomposed. We found a significant correlation between biomass P and P uptake by kidney beans. Therefore, biomass P may serve as a reliable indicator of P availability in Andosols.

Discipline: Soil, fertilizers and plant nutrition
Additional key words: excess input of phosphorus, high phosphorus retention capacity, optimum phosphorus fertilizer application rate

Introduction

The average application rate of phosphorus (P) fertilizer to agricultural fields in Japan is about 120 kg P_2O_5/ha[22]. This high P application rate is attributed to low P fertilizer use efficiency (about 20%) in Japan[26]. This low efficiency is due to the characteristics of Andosols, which are widely distributed (about 50% by area) in upland fields in Japan.

Andosols have low bulk density[21] and enhanced content of exchange complexes, such as allophane, imogolite, and aluminum-humus[32]. Due to the accumulation of active forms of aluminum and iron, Andosols have a high P sorption capacity[21] and thus require a high P application rate. For example, the standard rate of P application for maize (*Zea mays*) grown in Andosols is 240 kg P_2O_5/ha, compared to 150 P_2O_5/ha in lowland soil.

Nishio[23] analyzed the relationship between P application rate and yield of major crops, and showed that yields of many crops did not increase at higher P application rates. Cordell et al.[10] estimated that global P reserves may be depleted in 50-100 years, amid increasing global demand for P. The shortage of natural P resources might have limited exports of rock phosphate, and the rising price of P fertilizer has adversely affected farm management. In addition, the application of excessive P causes problems such as inhibition of trace element uptake[33], environmental pollution[6], and outbreaks of soil-borne diseases[12].

Estimation of P availability

1. Methods for measuring the available P in soil

The application rate of P fertilizer is adjusted according to the amount of available P in soil. Inorganic P (Pi) extracted from soil is recognized as available P. Various methods have been proposed for measuring available P in soil, such as the Bray method Nos. 1 and 2[3], the Olsen method[27], and extraction with water[17].

Based on Japanese government recommendations, the Truog method[38] has been widely used in Japan for diagnos-

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Table 1. Correlation coefficients (*r*) between available P and plant P uptake

	Truog	Bray no.1	Bray no.2	Ca-Pi	Al-Pi	Fe-Pi
Sekiya[30]						
plant: wheat						
non-volcanic soil	-	-	-	0.99 **	0.25	-0.18
volcanic ash soil	-	-	-	0.81 **	0.45	0.10
Shoji et al.[31]						
plant: oats						
peat soil	0.84 **	0.98 **	0.96 **	0.75 **	-	-
alluvial and diluvial soil	0.61 *	0.60 *	0.73 **	0.65 *	-	-
Andosol	0.26	0.76 **	0.83 **	0.51	-	-
Minami et al.[20]						
plant: oats						
non-volcanic soil	0.87 **	0.62 *	0.61 *	0.63 *	0.49	0.29
volcanic ash soil	0.26	0.34	0.47	0.31	0.75 *	0.29

**$P < 0.01$, *$P < 0.05$

ing soil P fertility. As shown in Table 1, a significant correlation between Truog P and P uptake by oats (*Avena sativa*) has been demonstrated in non-volcanic soils[20,31]. Shoji et al.[31] analyzed the relationship between available P and P uptake by plants. Significant positive correlations (P<0.01 or P<0.05) were obtained between Truog P and plant P uptake in peat, alluvial, and diluvial soils[31]. These results suggest that Truog P is suitable for estimating available P in non-volcanic soils.

2. Problem in estimating P availability in Andosols

In Andosols, Truog P is not correlated with plant P uptake (Table 1). Several studies have examined which method is most appropriate for evaluating available P correlated with plant P uptake in volcanic soils. For example, Shoji et al.[31] proposed P extracted by both Bray method Nos. 1 and 2[3], Minami et al.[20] proposed aluminum-bound Pi, and Sekiya[30] proposed Ca-Pi as the best indicator of available P.

Kato et al.[14] estimated available P in Andosol using the isotopic exchange method and compared the results to those obtained with chemical extract methods, namely, the Truog method and the Bray No. 2 method[3]. Both Truog P and Bray P were two to three times higher than P estimated by the isotopic exchange method, and neither correlated with plant P uptake.

Therefore, the results of numerous studies suggest that available P estimated by chemical extract methods, including the Truog method, is not a suitable indicator of plant P uptake. An improved method for evaluating soil P availability for plants is needed to determine optimum P fertilizer application rates for Andosols.

Soil microbial biomass P as an indicator of P availability in Andosols

1. Soil microbial biomass P as a P source for plants

Organic P accounts for 35–65% of total P in soil[13]. Inositole, the main form of organic P in soils, is much more abundant in soils (>30%) than microbes (<10%)[34]. However, the central component of the soil organic P cycle is thought to be related to P contained in soil microbes[34]. Soil microbes not only decompose organic P, they also store P. Kouno[15] estimated that P accounts for 5.9% of the elements in microbes. The average P content in soil microbes was calculated to be 80 mg P/kg of dry soil[11], and Brookes et al.[5] calculated the mean annual flux of P through soil microbes in upland field soils in England to be 7 kg P/ha/year.

Of microbial intracellular P, >60% is usually in the form of nucleic acids, 20% comprises acid-soluble P-esters, and 5% phospholipids[39]. These P compounds are thought to exist mainly in the cell cytoplasm as Pi or on the cell membrane. Marumoto[19] showed that the amount of available P released in soil by chloroform fumigation is closely related to the P content of soil microbes. Accordingly, the P in soil microbes may be released directly from cells when microbes die, or easily decomposed, and become readily available to plants[5,34]. Kouno et al.[16] estimated that the turnover time of biomass P (37 days) was about half that of biomass carbon (biomass C; 82 days). These results suggest that biomass P should be both quantitatively and qualitatively assessed as an important P source for plants.

2. Soil microbial biomass P as an indicator of available P

Biomass P constitutes a key part of the soil P pool

Table 2. Correlation coefficients (*r*) between biomass P or available P and plant P uptake

	plant	Biomass P	NaOH P	$NaHCO_3$ P	Resin P	Bray P
Saini et al.[28]						
Ustochrepts	sorghum	0.89 **	-	-	-	-
	chickpea	0.97 **	-	-	-	-
Ayaga et al.[2]						
Andosol	maize	0.84 *	NS	NS	NS	-
Acrisol	maize	0.95 *	NS	NS	NS	-
Chen et al.[8]						
Red soils [a]	ryegrass	0.94 **	-	-	-	0.96 [b] **

NS: not significant, $^{**}P < 0.01$, $^{*}P < 0.05$
- : not analyzed
[a] Oxisoils, Ultisols, and Alfisols
[b] Measured by Bray No. 1 method[3]

available for plants. Recent studies have reported significant correlations (P<0.01) between biomass P and P uptake by plants (Table 2), such as maize[2], sorghum (*Sorghum bicolor*) and chickpea (*Cicer arietinum*)[28], growing in fields with low soil P content. These findings suggest that microbial biomass is a key P source in upland soils with low P availability.

Chen et al.[8] conducted pot experiments using red soils (Oxisols, Ultisols, and Alfisols) of various P fertility and found a significant positive correlation (P<0.01) between biomass P and P uptake by ryegrass (*Lolium* spp.). In a previous field experiment in Hokkaido, we also examined the relationships between P uptake by kidney bean (*Phaseolus vulgaris* cv. Taisho-kintoki) and biomass P and Truog P in an Andosol field where all treatments contained sufficient P[36]. The P content of shoots at harvest correlated significantly (P<0.01) with biomass P but not with Truog P (Fig. 1). These results suggest that biomass P is an important P source, irrespective of P availability in soil, and could serve as a reliable indicator of soil P availability for plants.

Future perspectives

Biomass P may be an important indicator of P fertility in Andosols, which exhibit high P fixation. If biomass P were used to evaluate soil P availability, the excess input of P fertilizer could be reduced. However, studies have shown a positive correlation between biomass P and P uptake in only a few plants, and field experiments are needed to test a wider array of species. The accuracy of biomass P as an indicator of P fertility may depend on conditions such as soil Pi contents, soil type, and the growing season of plants, and these conditions must also be tested in future research.

Biomass P is usually analyzed by the chloroform fumigation extraction method[4]. Although Sugito et al.[35] proposed a way to improve chloroform fumigation extraction

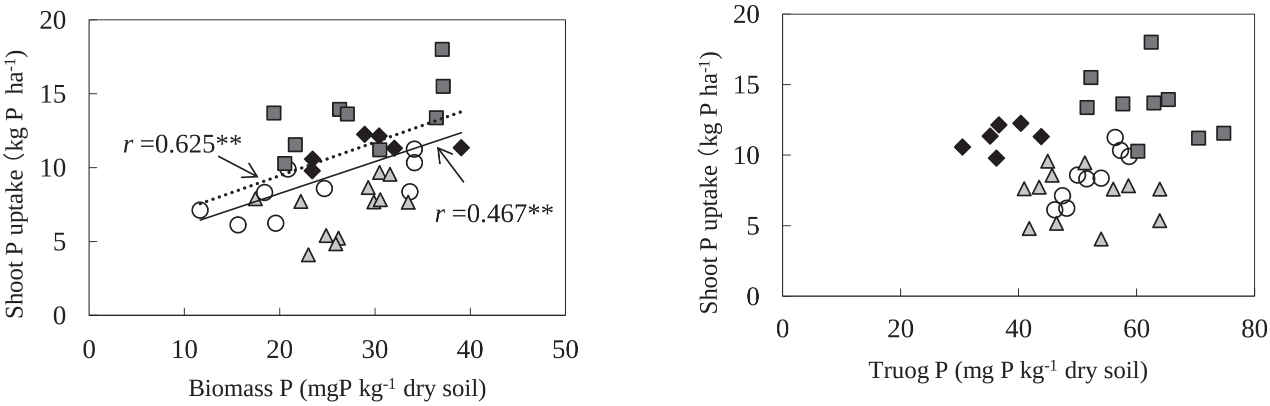

Fig. 1. Relationships of shoot P uptake by kidney bean (*Phaseolus vulgaris* cv. Taisho-kintoki) with biomass P and Truog P in an Andosol field

Pearson's correlation coefficients are shown, and regression curves and r values are shown only for the significant correlations ($^{**}P$<0.01). Solid line: regression curve for 4-year data; dotted line: regression curve for 2004, 2005, and 2007. n = 6 in 2004, 9 in 2005 and 2007, and 12 in 2006.

for measuring biomass P in upland Andosol fields, the chloroform fumigation extraction method is laborious and time-consuming. A simple method to estimate biomass C by measuring soil ATP was proposed[24], likewise one of substrate-induced respiration[1]. However, it is difficult to estimate biomass P using this simple method because the biomass C/P ratio is not constant. For example, Brookes et al.[5] reported that the biomass C/P ratio ranged from 10.6 to 35.9, while Sarathchandra et al.[29] reported values of 15 to 63. Consequently, a simple method to accurately estimate biomass P is needed.

Cole et al.[9] conducted simulation experiments to identify the flow of P among soil components (Fig. 2). The results suggested that considerable amounts of P flow from soil water to soil microbes, from soil microbes to labile organic P, and from labile organic P to soil water (shown as shaded arrows in Fig. 2). Thus, increasing P uptake by microbes is likely to decrease P fixation in soil and change it to a stable inorganic form (shown as dotted arrows in Fig. 2). Increasing biomass P may increase the efficiency of P fertilizer[2,25], especially in soils with high P retention capacity, such as Andosols, meaning it is also important to establish a soil management method for increasing biomass P.

The application of organic matter, such as glucose[16], crop residues[18], and cow manure[37], increases biomass P. An exception was reported by Takeda et al.[37], who showed that biomass P was significantly (*P*<0.05) higher in soil to which residues of cereal rye (*Secale cereale*) had been applied than in the control (no residues applied), whereas the application of residues of rapeseed (*Brassica napus*) did not increase biomass P compared to the control. One reason seemed to be the difference in the ratio of C, nitrogen (N), and P in the two plant residues. Therefore, future research should also investigate how the ratios of C, N, and P in organic matter affect biomass P with a view toward devising methods of organic matter application that will increase biomass P.

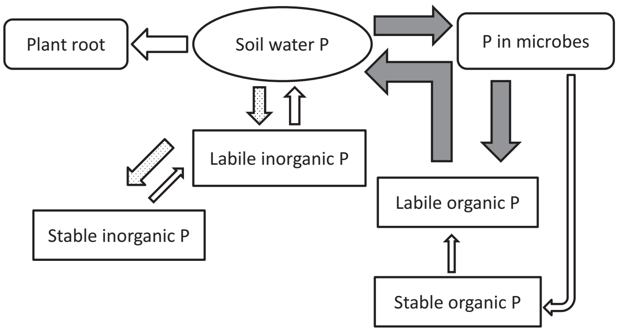

Fig. 2. A tentative scheme of P flow among soil components
The thickness of the arrow roughly represents the magnitude of P flow. Modified after Chauhan et al.[7]

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