

Available phosphorus declines in organic residues-treated sandy soils indicating its transformation to more slowly available forms for phosphorus conservation

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ABSTRACT: Reducing fertilizer phosphorus (P) input in the face of global P exhaustion is desirable. This study investigated the effects of long-term application of different quality plant residues on changes in available P concentrations in a tropical coarse-textured soil. Five residue treatments were annually applied to the sandy Khorat soil including (i) unamended (control, CT), two legume residues including (ii) groundnut (GN) stover and (iii) leaf + petiole litter of tamarind (TM), and two non-legume residues including (iv) rice straw (RS) and (v) leaf litter of dipterocarp (DP). After 20 years of residue application, available P concentrations in legumes (25.9 mg kg⁻¹ for GN and 26.8 mg kg⁻¹ for TM) were comparable to the CT (29.2 mg kg⁻¹), but they were lower in the non-legumes (14.2 mg kg⁻¹ for RS and 16.9 mg kg⁻¹ for DP). Soil organic carbon content had positive effects on available P concentrations ($r^2 = 0.770^{***}$) as did the exchangeable Ca ($r^2 = 0.461^*$). The negative effects were found in pH ($r^2 = 0.386^*$) and exchangeable K concentrations ($r^2 = 0.605^{**}$). The results highlighted the influence of soil organic matter (SOM) and Ca in sustaining P in the potentially available forms in tropical coarse-textured soils. Possible mechanisms underlying effects of SOM and other related soil properties on changes in soil available P are discussed.

Keywords: Basic cations, Potentially available phosphorus, Residue quality, Soil organic matter, Sustainability

Introduction

The majority of phosphorus (P) used in crop production is mined from a finite source, rock phosphate (apatite). It is not yet widely known that the supply of P could be exhausted globally in the next 40 – 400 years (Obersteiner et al., 2013). It is estimated that in the US domestic sources may be exhausted within a few decades while in other countries that have larger reserves, such as Morocco and China, these may run out within a century (Vaccari, 2009). Thailand imported almost half a million tons of P fertilizer (P₂O₅) in 2014 (FAOSTAT, 2017). Reducing fertilizer P use through more effective recycling of soil P can be achieved by application of organic materials

which is not only a source of P but also an agent of transformation of inorganic to organic forms of P (Weil and Magdoff, 2004). The use of organic materials is particularly imperative in the tropics where soils are generally sandy and acid, and the decomposition rate is rapid resulting in low soil organic matter (SOM) (Sanchez and Logan, 1992). While a number of short-term studies on the influence of organic amendments on P in soils exist, to the best of the authors' knowledge, there have been few long-term studies, which are important to evaluate changes and sustainability of P in tropical sandy soils. Some long-term studies in the temperate zone were focused on the effects of animal manures, which have high P contents, on soil P. For example, the effects of application

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of animal manures on soil P status was monitored for 33 years in a calcareous clay loam soil of Alberta of Canada (Ojekami et al., 2011), for 17 years in different textured soils of southern and central parts of the Netherlands (Salm et al., 2017), and for 15 years in a sandy loam soil in Alabama in the USA (Ranatunga et al., 2013). In the tropics, application of animal manures for 8 years in a sandy loam soil of Rio Grande do Sul of Brazil was studied by Couto et al. (2017) and the effects of application of other organic material sources of P, including plant residues, was studied for 3 years in a red clayey soil of a highland of western Kenya. It showed that their quality (chemical composition), notably the ratio of soluble C to P, controlled soil P availability (Nziguheba et al., 2000). Although a short-term (8 weeks) incubation experiment showed that application of organic residues transformed fertilizer P into labile and stable organic P pools resulting in improving soil P cycling and fertility (Reddy et al., 2005), long-term studies on the effects of application of organic materials which change SOM content and associated P forms in the tropics are lacking. Therefore, the objective of this study was to investigate effects of long-term application of different quality plant residues on changes in available soil P concentrations in a tropical coarse-textured soil.

Materials and methods

A long-term experiment in which different quality organic residues were applied annually for 20 years (1995 to 2014) was conducted. The study site was located at a research station at Tha Phra sub-district of Khon Kaen province in North-east Thailand (16° 20' N; 102° 49' E). The initial properties of the Khorat series soil were sandy

texture (93.4% sand, 4.5% silt and 2.1% clay), 1.45 g cm⁻³ in bulk density, pH 5.5; and concentrations of the following soil parameters including 2.09 g kg⁻¹ soil organic carbon (SOC), 0.2 g kg⁻¹ total N, 47.2 mg kg⁻¹ Bray II extractable P, 30.1 mg kg⁻¹ exchangeable K, and 3.53 cmol kg⁻¹ cation exchange capacity (CEC) (Vityakon et al., 2000). A randomized complete block design with three replications was used. Five treatments of contrasting quality plant residues comprised (i) unamended (control, CT), two legume residues including (ii) groundnut (*Arachis hypogaea*) (GN) stover and (iii) leaf + petiole litter of tamarind (*Tamarindus indica*) (TM), and two non-legume residues including (iv) rice (*Oryza sativa*) straw (RS) and (v) leaf litter of dipterocarp (*Dipterocarpus obtusifolius*) (DP). Annually in May, the residues were applied at the rate of 10 Mg ha⁻¹ (equivalent to 1.6 t rai⁻¹) dry weight to the topsoil (0 to 15 cm) in a 4x4 m² plot. Weeds were manually removed at about monthly interval. Soils employed in this study were sampled from the topsoil at the end of the years 2, 6, 11, 16, and 20.

Chemical analyses for nutrient (K, Ca, Mg, and Na) concentrations in the residues, employed the dry-ashing method (Miller, 1998) followed by their determination using a flame atomic absorption spectrophotometer (novAA[®] 350, Analytik Jena, Germany). Data of nutrient concentrations of the residues were means of those employed as soil amendment in years 16, 18, and 20 (Table 1).

Soil organic carbon (SOC) was determined by the wet digestion method of Walkley and Black, pH in a soil slurry of a soil: H₂O ratio of 1:2.5 by a pH meter, available P extracted by Bray II (0.1 M HCl + 0.03 M NH₄F, pH 1.5) solution and determined colorimetrically by a spectrophotometer (Spectro SC, Labomed. Inc, Culver City, California, USA) at the wavelength 820 nm, while exchangeable

cations, i.e., K, Ca, Mg, and Na, were extracted by 1 M NH₄OAc at pH 7.0 and determined by a flame atomic absorption spectrophotometer (Flame AAS novAA[®] 350, Analytik Jena, Germany).

Table 1 Selected nutrient contents in plant residues used in this study.

Residue	K	Ca	Mg	Na
	----- (g kg ⁻¹) -----			
RS	14.38 ± 2.20 †	4.21 ± 0.79	1.29 ± 0.11	1.04 ± 0.39
GN	25.05 ± 9.44	21.13 ± 5.66	6.05 ± 0.58	0.69 ± 0.17
DP	3.68 ± 1.09	7.92 ± 1.40	3.07 ± 0.58	0.31 ± 0.05
TM	6.24 ± 0.68	34.95 ± 6.84	4.53 ± 1.04	0.44 ± 0.01

† Values are mean ± standard error of the mean (n = 3).

A one-way analysis of variance based on randomized complete block design was used to evaluate effects of residues on available soil P concentrations. Mean comparisons were performed using the least significant difference (LSD) method. Relationships between available P concentrations and their potentially influencing soil parameters, i.e., SOC, pH, K, Ca, Mg, and Na, were determined using Pearson correlation coefficient (*r*) and simple regression analysis (*r*²). Significant differences were at *p* ≤ 0.05. The statistical analyses were performed using IBM SPSS Statistics version 20 (IBM World Trade Corporation, Barbados).

Results and discussion

Available soil P concentrations, from years 0 – 11, mostly decreased with time in all treatments, and were quite stable after year 11 onwards with exception for non-legume residues, i.e., RS and DP, which still gradually decreased after year 11 (Figure 1). In RS and DP, available P concentrations showed a tendency to decline from year 6 onwards. This can be seen in P concentrations of RS which decreased significantly relative to the control (CT) from year 6 while that of DP occurred from year 16 onwards. Residual chemical fertilizer from previous experiments resulted in relatively

high available P concentrations in all organic residue treatments in the earlier years than the later years (Rungthong, 2016). In addition, P in weed biomass removed at regular intervals from the experimental plots caused a decline in P concentrations in all residue treatments. That CT had highest available P concentration was due to lesser weed biomass removed from this treatment relative to those receiving residues, i.e., weed biomass of 6 g m⁻² in the former vs 40-90 g m⁻² in the latter treatments at the end of year 15 (P. Vityakon, unpublished data). Additionally, under CT there was a higher population of phosphate solubilizing bacteria, e.g., *Pseudomonas*, *Azospirillum*, *Burkholderia*, and *Bacillus* than the treatments receiving residues (Rungthong, 2016). Higher populations of the phosphate solubilizing bacteria in CT than the residue amended treatments could have brought about higher phosphatase activity in the former than the latter treatments. Soil organic matter (SOM) both humic substances (e.g., humic acids and fulvic acids) and non-humic substances (e.g., proteins and tannins) as well as dissolved organic matter which were higher in residue treatments than CT could decrease phosphatase activity via SOM-enzyme complexation as revealed by Adamczyk et al. (2009) and Staunton et al. (2012).

Pearson correlation and simple regression analyses between available P concentrations and various soil properties revealed that P was highly significantly correlated with SOC content ($r = 0.877^{***}$; $r^2 = 0.770^{***}$; $P = -7.247 + 9.803 \text{ SOC}$) (Table 2). Several mechanisms are proposed on influence of soil organic matter (SOM) on available P in soils. Firstly, SOM is an important source of P (Weil and Magdoff, 2004.). Secondly, SOM-derived organic anions, such as malate, citrate, and tartrate, could bind with Al and Fe oxides, thus reducing P fixation (Hue and Amien, 1989). Thirdly, SOM increased growth and activity of microorganisms producing phosphatase which is

the enzyme involving in organic P mineralization (Kunze et al., 2011). Fourthly, organic P was a constituent of SOM in soil aggregates (Li et al., 2016; Ranatunga et al., 2013) as SOM is a major cementing agent for soil aggregate formation (Puttaso et al., 2013). These mechanisms serve to enhance contents of potentially available P forms in soils. Higher SOM contents of legumes (i.e., GN and TM) than non-legumes (i.e., RS and DP) were reported by Xayavong (2017). This was supported by the current study that GN and TM which produced higher SOM contents had higher available P concentrations than RS and DP.

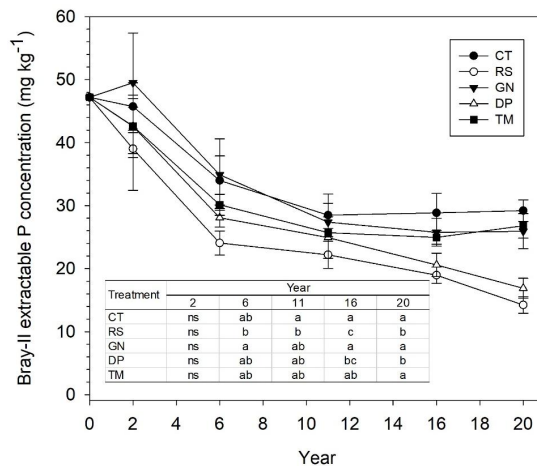


Figure 1 Available P concentrations as affected by different quality residues in the sandy textured Khorat soil. Error bars represent standard error of the mean. Small letters in the inset table show comparisons among means. Those means in the curves of the same time interval accompanied by common letters in the same column are not significantly different ($p \leq 0.05$) (LSD).

Positive effects of soil Ca on available P concentration were revealed by significant positive correlation ($r = 0.679^*$) (Table 2) and regression ($r^2 = 0.461^*$; $P = 10.37 + 0.058 \text{ Ca}$). On the other hand, K had negative effects on available P concentrations which can be seen in significant negative correlation ($r = -0.778^{**}$) and regression ($r^2 = 0.605$; $P = 31.68 - 0.228 \text{ K}$). Soil aggregation is enhanced through Ca, a polyvalent cation,

which promotes flocculation of soil colloid (Mengel and Kirkby, 1987) resulting in increasing P content in aggregates. In addition, Ca acts as a bridge of SOM-soil particle complex in aggregate formation (Lützow et al., 2006). On the other hand, K, a monovalent cation, deflocculates soil colloid and hence works against aggregate formation (Mengel and Kirkby, 1987).

Table 2 Pearson correlation coefficients of available P with soil organic carbon (SOC) , pH, and exchangeable cations (K, Ca, Mg, and Na) in the sandy textured Khorat soil amended with different quality residues at year 20 †.

	SOC	pH	K	Ca	Mg	Na
Bray II extractable P	0.877***	-0.621*	-0.778**	0.679*	0.100 ^{ns}	-0.214 ^{ns}

* $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$; ns, not significantly different.

† Concentrations of soil elements (K, Ca, Mg, and Na) are designed as g kg^{-1} , available P as mg kg^{-1} , and SOC as g kg^{-1} .

The negative effect of soil pH on available P concentrations, which was shown by their significant negative correlation ($r = -0.621^*$) (Table 2) and regression ($r^2 = 0.386^*$; $P = 56.22 - 6.20 \text{ pH}$), was likely due to the influence of increases in soil pH on decreasing soluble Al and Fe contents with consequent decreases in complex formation with P (occluded P) (Ch'ng et al., 2014; Mengel and Kirkby, 1987). An increase in pH also increases phosphatase activity (Dick et al., 2000) leading to increased available P concentrations. The increased available P was likely taken up by weeds which are removed from the soil resulting in P loss.

Conclusions

Our results showed clearly that none of the plant residues (both legumes [GN and TM] and non-legumes [RS and DP]) increased available P concentration through time. However, the residues, notably the legumes, increased SOM which indicates that P was transformed through various mechanisms into potentially available forms which could sustain soil P in the long term. This has implications for conserving soil P in potentially available forms and, hence, reducing fertilizer P inputs. Appropriate quality plant residues should be selected for the purpose of enhancing long-term P availability. Such plant residues are identical to those that enhance SOM accumulation. Our study

highlighted the importance of Ca contents of plant residues in increasing available P through enhancing SOM accumulation.

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References

- Adamczyk, B., V. Kitunen, and A. Smolander. 2009. Polyphenol oxidase, tannase and proteolytic activity in relation to tannin concentration in the soil organic horizon under silver birch and Norway spruce. *Soil Biol. Biochem.* 41: 2085-2093.
- Ch'ng, H. Y., O. H. Ahmed, and N. M. A. Majid. 2014. Improving phosphorus availability in an acid soil using organic amendments produced from agroindustrial wastes. *Sci. World J.* Article ID 506356. doi: 10.1155/2014/506356.

- Couto, R.d.R., P.A.A. Ferreira, C.A. Ceretta, C.R. Lourenzi, D.B. Facco, A. Tassinari, R. Piccin, and L.D. Conti. 2017. Phosphorus fractions in soil with a long history of organic waste and mineral fertilizer addition. *Bragantia* 76(1): 1678-4499.
- Dick, W.A., L. Cheng, and P. Wang. 2000. Soil acid and alkaline phosphatase activity as pH adjustment indicators. *Soil Biol. Biochem.* 32(13): 1915-1919.
- FAOSTAT. 2017. Food and agriculture data. Food and Agriculture Organization of the United Nations. Available: <http://www.fao.org/faostat/en/#data>. Accessed Aug. 9, 2017.
- Hue, N.V., and I. Amien. 1989. Aluminum detoxification with green manures. *Commun. Soil Sci. Plant Anal.* 20(15-16): 1499-1511.
- Kunze, A., M.D. Costa, J. Epping, J.C. Loffaguen, R. Schuh, and P. E. Lovato. 2011. Phosphatase activity in sandy soil influenced by mycorrhizal and non-mycorrhizal cover crops. *Rev. Bras. Ciênc. Solo.* 35(3): 705-711.
- Li, B., T. Ge, H. Xiao, Z. Zhu, Y. Li, O. Shibistova, S. Liu, J. Wu, K. Inubushi, and G. Guggenberger. 2016. Phosphorus content as a function of soil aggregate size and paddy cultivation in highly weathered soils. *Environ. Sci. Pollut. Res. Int.* 23(8): 7494-7503.
- Lützow, M.v., I. Kögel-Knabner, K. Ekschmitt, E. Matzner, G. Guggenberger, B. Marschner, H. Flessa. 2006. Stabilization of organic matter in temperate soils: Mechanisms and their relevance under different soil conditions – A review. *Eur. J. Soil Sci.* 57: 426-445.
- Mengel, K., and E.A. Kirkby. 1987. Principles of Plant Nutrition, 4th edition. International Potash Institute, Worblaufen-Bern.
- Miller, R.O., 1998. High temperature oxidation: Dry ashing. pp. 53-56. In: Y.P. Kulra. Handbook of Reference Methods for Plant Analysis. Soil and Plant Analysis Council Inc. CRC Press, Boca Raton.
- Nziguheba, G., R. Merckx, C. A. Palm, and M.R. Rao. 2000. Organic residues affect phosphorus availability and maize yields in a Nitisol of western Kenya. *Biol. Fert. Soils* 32: 328–339.
- Obersteiner, M., J. Penuelas, P. Ciais, M. van der Velde, and I.A. Janssens. 2013. The phosphorus trilemma. *Nature Geosci.* 6(11): 897-898.
- Ojekami, A., D. Ige, and X. Hao. 2011. Phosphorus mobility in a soil with long term manure application. *J. Agric. Sci.* 3(3): 25-38.
- Puttaso, A., P. Vityakon, F. Rasche, P. Saenjan, V. Treloges, and G. Cadisch. 2013. Does organic residue quality influence carbon retention in a tropical sandy soil? *Soil Sci. Soc. Am. J.* 77(3): 1001-1011.
- Ranatunga, T.D., S.S. Reddy, and R.W. Taylor. 2013. Phosphorus distribution in soil aggregate size fractions in a poultry litter applied soil and potential environmental impacts. *Geoderma.* 192: 446-452.
- Reddy, D.D., S.A. Rao, and M. Singh. 2005. Changes in P fractions and sorption in an Alfisol following crop residues application. *J. Plant Nutr. Soil Sci.* 168: 241-247.
- Rungthong, R. 2016. The effects of legume residues with and without allelopathic substances on soil properties and biodiversity of plant growth promoting bacteria. M.S. Thesis. Khon Kaen University. Khon Kaen. (in Thai with English abstract).
- Salm, C.v.d., J.C.v. Middelkoop, and P.A.I. Ehlert. 2017. Changes in soil phosphorus pools of grasslands following 17 yrs of balanced application of manure and fertilizer. *Soil Use Manage.* 33: 2-12.
- Sanchez, P.A., T.J. Logan. 1992. Myths and science about the chemistry and fertility of soils in tropics. pp. 35-46. In: R. Lal and P.A. Sanchez. Myths and Science of Soils of the Tropics. SSSA Special Publication No. 29. SSSA Inc. and ASA Inc. Madison, Wisconsin.
- Staunton, S., R. Razzouk, J. Abadie, and H. Quiquampoix. 2012. Water-extractable soil organic matter inhibits phosphatase activity. *Soil Biol. Biochem.* 55: 14-16.
- Vaccari, D.A. 2009. Phosphorus: A looming crisis. *Sci. Am.* 300(6): 54-49.
- Vityakon, P., S. Meepetch, G. Cadisch, and B. Toomsan. 2000. Soil organic matter and nitrogen transformation mediated by plant residues of different qualities in sandy acid upland and paddy soils. *Neth. J. Agric. Sci.* 48: 75-90.
- Weill, R., and F. Magdoff. 2004. Significance of soil organic matter to soil quality and health. pp. 1-43. In: F. Magdoff and R. Weill. Soil Organic Matter in Sustainable Agriculture. CRC Press, Boca Raton.
- Xayavong, S. 2017. Changes in soil chemical properties affect plant growth under 20-year applications of contrasting quality organic residues with and without chemical fertilizer. M.S. Thesis. Khon Kaen University, Khon Kaen.