

LAND-USE CHANGES AFFECTING PHOSPHORUS DISTRIBUTION IN SOIL PROFILE IN NORTHEAST THAILAND

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Abstract

The objective of this study was to investigate distribution of phosphorus (P) in different soil profiles as influenced by land-use changes. The study sites were located in six districts of the Maha Sarakham province, Northeast Thailand. Soil samples were collected from five soil depths: 0-20, 20-40, 40-60, 60-80, and 80-100 cm under four adjacent land uses, including forest, cassava, sugarcane, and rice paddy. The air-dried soil samples were subjected to determine available P using a Bray II extractant. The concentration of P was then measured employing a UV-VIS spectrophotometer. When considering P stock at each soil layer, higher P stock was in topsoil (0-20 cm) than in each of the 5 layers of subsoils. Agricultural practices, such as high rate of chemical fertilizer input, can enhance P stocks in soils of upland crops (i.e., sugarcane and cassava), in comparison to paddy and forest soils. Additionally, deep plowing in the upland soils prior to cultivation can induce P leaching from topsoil to subsoil, as seen in the larger amount of P accumulation in the upland subsoil. This study pointed out that the same land use, with different agricultural practices from farmers, could lead to different patterns of P distribution in topsoil and subsoil. To restore P in agricultural soil, fertilizer management for crop cultivation is needed.

Keywords: *Deciduous dipterocarp forest, available phosphorus, land-use change, soil depth, Northeast Thailand*

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Introduction

Land-use change and intensive farming are the predominant global changes of this century. This is mainly due to the global socio-economic demand for food, livestock feed, fiber and biofuel, which is driven by population growth (Geissen *et al.*, 2009; Guillaume *et al.*, 2015). Intensive agricultural practices including high-yielding crop varieties, fertilization, irrigation, and pesticides leads to the degradation of soil properties. As agricultural land becomes further degraded, more forests are cleared and converted for the needed agricultural production. This has led to a considerable decrease of tropical forest area worldwide, especially in Southeast Asian countries (Gatto *et al.*, 2015; Tarigan *et al.*, 2015).

In 1973, Northeast Thailand had a total land and forest area of 16,771,793 and 5,067,100 ha (Royal Forest Department, 2019). The forest area accounted for 30% of the total land area of this region. Recently in 2017, forest area decreased to 2,504,889 ha (-49% of the total forest area in 1973). Deciduous dipterocarp is the most widespread forest type of Northeast Thailand. Over the last few decades, forests were converted to monoculture plantations, especially rice paddy, cassava, sugarcane and rubber. As a result, extensive conversion of natural ecosystems to plantation leads to decreasing soil fertility and subsequent soil degradation (Guillaume *et al.*, 2016).

Land-use change significantly modifies the physical, chemical and biological soil properties, affects soil fertility, and increases erosion and compaction (Matson *et al.*, 1997; Geissen *et al.*, 2009; Moges *et al.*, 2013). Phosphorus (P) is a key nutrient requiring attention in response to land-use change (Garcia-Montiel *et al.*, 2000). It is the most limiting nutrient for plant productivity, particularly in tropical regions (Sanchez, 1976; Vitousek, 1984; Holford, 1997; Wright, 2009; Dieter *et al.*, 2010; Spohn and Kuz'yakov, 2013). Wright (2009) reported that land-use changes affect P status in soil. There have been many studies focusing on the amount of P in different land uses. For instance, Groppo *et al.* (2015) reported that P stock was higher in crop

rotation (soy or corn in summer and *L. multiflorum* or oats in winter) than in forest and pasture soils. Likewise, Sheklabadia *et al.* (2014) revealed that labile P levels were higher in wheat than in forest soils. In addition, Lilienfein *et al.* (2000) found that conventional tillage and no-till maize-soybean soils had higher P content than degraded and productive pasture soils, whereby P was removed by grazing. Thus, P fertilizer application to soil during cultivation enhanced P levels in agricultural lands. In contrast to Slazak *et al.* (2010), they also reported that pine-oak forest had higher total and labile P than arable soils. They suggested that decomposition of litterfall led to releasing P to soil. Although P is one of the main limiting nutrients for agricultural productivity in the tropics, the effect of land-use change on P distribution in tropical sandy soil profile remains unclear.

Rice paddy and upland field crops are major crops of the current study site. Distribution of P under these rice paddy and upland crop systems may be inherently different. That is, paddy soils are under periodically anaerobic and temporarily aerobic conditions, while field crop soils (e.g., cassava and sugarcane) are totally under aerobic condition (Vityakon *et al.*, 2000). Moreover, forest soil might provide different patterns of P in soil profiles. Conversion from forest to agricultural lands might differently contribute to P accumulation patterns in their top and subsoils. Therefore, this study was designed to determine land-use changes affecting the distribution of P in these soil levels.

Materials and Methods

Study Site and Soil Sampling

There were six study sites in the Maha Sarakham province of Northeast Thailand. The study sites included Muang, Kantharawichai, Kosum Phisai, Kut Rang, Borabue and Wapi Pathum districts, shown in Figure 1. At each site, four adjacent land uses including secondary *Deciduous dipterocarp* forest, cassava converted

from the forest for about five years, sugarcane converted from the forest for about seven years, and paddy lands converted from the forest for >15 years were employed in this study. The average land altitudes above sea level for forest, cassava, sugarcane, and paddy were 185, 185, 184, 178 m, respectively. *Deciduous dipterocarp* species were dominant in all forest locations in this study. According to farm owner interview, the agronomic practices for cassava, sugarcane, and rice paddy were different among the locations.

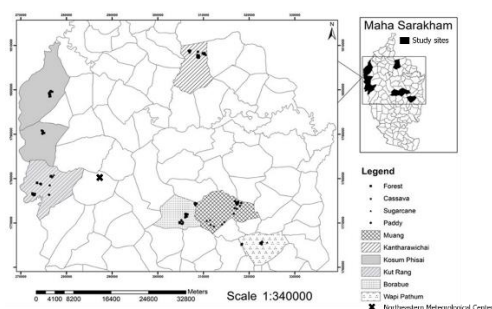


Figure 1. A map presenting study sites in the Maha Sarakham province of Northeast Thailand

Cassava (Kasetsart50 or KU50) was grown in the early rainy season (May to June). Nitrogen fertilizer as urea (46-0-0) was applied to the crop at the rate of 113 kg ha⁻¹ at planting and fertilizer formula 15-15-15 of N-P-K at the rate of 313 kg ha⁻¹ was applied three months after planting (MAP). The crop was harvested during March to May of the following year. Green and cattle manures were also added in some years in Wapi Pathum location only. Sugarcane (KK3) was grown in the late rainy season during October to February. Fertilizer formula 15-15-15 of N-P-K was added to the crop at the rate of 313-469 kg ha⁻¹ for each split was added to the crop at two splits at planting and at 4 to 6 MAP. Cattle manure was also added in some years in most locations except in Kusum Phisai and Kut Rang locations. Glutinous rice (RD6) and non-glutinous rice (KDML 105) were transplanted in June. Fertilizer in a form of formula 16-16-8 of N-P-K was applied to crop

at the rate of 125-156 kg ha⁻¹ at tillering. The crop was harvested during November to December.

Regarding to farmer interview, farmers at all locations burned rice stover and sugarcane leaves in the years when the stover and sugarcane leaves were too high. The farmers did not burn cassava leaves. The fertilizer rates applied to the crops for each location were provided in the ranges because the farmers did not know the exact rates in each year.

Precipitation and temperature during soil sampling periods are briefly described. Average monthly precipitation and temperature over the soil sampling periods (July 2017-June 2018) are revealed in Figure 2. This climatic information was received from the Northeastern Meteorological Center in the Maha Sarakham province. Monthly average rainfall and temperature of the study site was similar in which the double-bell shaped pattern dropped during November-February. The precipitation was high during July-October 2017 and April-May 2018.

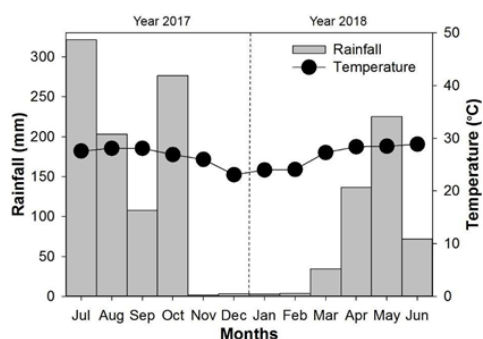


Figure 2. Average rainfall and temperature during July 2017-June 2018

Soil samples were collected in a dry season in March 2018. Five soil depth intervals were collected from each sampling point, namely 0-20, 20-40, 40-60, 60-80 and 80-100 cm. Soil samples were air-dried and passed through a 2-mm sieve for further P analyses. The studied soils were classified as Nam Phong (Grossarenic Haplustalfs), Khorat (Typic Kandistults), Ubon (Grossarenic Halpustalfs),

Table 1. Some physical characteristics of the studied soils

Soil series	Soil classification ⁴	Soil depth (cm)	Particle (%)			Texture
			Sand	Silt	Clay	
Nam Phong ¹	Grossarenic Haplustalfs	0–20	90.9	6.5	2.6	Sand
		20–40	90.9	6.5	2.6	Sand
		40–60	91.2	2.1	6.7	Sand
		60–80	91.2	2.1	6.7	Sand
		80–100	91.2	2.1	6.7	Sand
Khorat ²	Typic Kandistults	0–20	79.3	13.5	7.2	Loamy sand
		20–40	77.5	11.4	11.1	Sandy Loam
		40–60	74.9	16.7	8.4	Sandy Loam
		60–80	67.1	20.1	12.8	Sandy Loam
		80–100	57.7	19.9	22.4	Sandy clay loam
Ubon ²	Grossarenic Halpustalfs	0–20	72.6	19.4	8.0	Sandy Loam
		20–40	69.2	18.0	12.8	Sandy Loam
		40–60	61.5	22.5	16.0	Sandy Loam
		60–80	65.0	21.4	13.6	Sandy Loam
		80–100	59.2	21.0	19.5	Sandy Loam
Roi Et ²	Aeric Kandiaquults	0–20	73.9	16.9	9.2	Sandy Loam
		20–40	74.9	12.3	12.8	Sandy Loam
		40–60	75.5	11.3	13.2	Sandy Loam
		60–80	70.8	13.6	15.6	Sandy Loam
		80–100	66.3	12.3	12.4	Sandy Loam
Satuk ³	Typic Paleustults	0–20	80.1	0.7	19.2	Sandy Loam
		20–40	N/A	N/A	N/A	N/A
		40–60	N/A	N/A	N/A	N/A
		60–80	N/A	N/A	N/A	N/A
		80–100	N/A	N/A	N/A	N/A

N/A: not available. ¹ Toung *et al.* (2000); ² Saenya *et al.* (2015); ³ Kawee Wong *et al.* (2013); ⁴ Soil Survey Staff (2014).

Roi Et (Aeric Kandiaquults) and Satuk (Typic Paleustults) series (Table 1). The particle sizes of the soil series are shown in Table 1.

Soil Phosphorus Analysis

Available P was extracted from the air-dried soil using Bray II solution as extractant (Bray and Kurtz, 1945). The extracted P was measured calorimetrically, based on the reaction with ammonium molybdate and development of the molybdenum blue color. Then the amount of P was measured at 882 nm using a UV-VIS spectrophotometer (Shimadzu UV-1700, Pharmaspec, Shimadzu Corp., Japan).

Statistical Analysis

Statistical analyses were performed using Statistix 8.0 software (Analytical Software, Tallahassee, FL, USA). The data were checked for normality and homogeneity of variances to meet the assumptions for ANOVA. Location $\times$ land use $\times$ soil depth were analyzed. Means comparisons among the different locations, land uses and soil depths were carried out by least significant difference (LSD).

Results

Some Soil Physical Properties Throughout Soil Profile of Different Land Uses

Moisture and bulk density throughout the soil profile (0–100 cm) are revealed in Table 2. The soil bulk density and moisture ranged from 1.34 to 1.87 g cm⁻³ and 0.66 to 21.16%, respectively. Soil types, which were covered each land use, are shown in Table 2. In the Muang district, Nam Phong soil series covered forest and cassava land uses, meanwhile Roi Et soil series covered sugarcane and paddy land uses. In the Kantharawichai district, forest and cassava soils were Khorat and Nam Phong series, respectively, whereas soils under sugarcane and paddy land uses were Roi Et series. Khorat and Ubon soil series covered all land uses in the Kosum Phisai and Wapi Pathum districts, respectively. In the Kut Rang district, soils under forest and cassava land uses were Nam Phong series, while sugarcane and paddy land uses were Ubon and Satuk series, respectively. In the Borabue district, Khorat soil series covered forest and cassava

Table 2. Some physical properties in soil profile (cm) under different land uses

Districts	Land use types	Soil series	Bulk density (g cm ⁻³)					Soil moisture (%)				
			Soil depth (cm)									
			0-20	20-40	40-60	60-80	80-100	0-20	20-40	40-60	60-80	80-100
Muang	Forest	Nam Phong	1.60	1.50	1.49	1.54	1.55	1.57	1.41	1.80	2.41	3.01
	Cassava	Nam Phong	1.58	1.56	1.51	1.62	1.49	0.57	1.27	1.92	9.62	10.18
	Sugarcane	Roi Et	1.50	1.63	1.57	1.56	1.62	1.45	1.12	1.27	2.21	5.55
	Rice paddy	Roi Et	1.69	1.68	1.76	1.78	1.87	4.15	5.05	10.79	11.22	11.32
Kantharawichai	Forest	Khorat	1.55	1.61	1.59	1.58	1.59	3.95	2.92	3.33	3.94	4.28
	Cassava	Nam Phong	1.54	1.59	1.63	1.59	1.60	10.60	3.85	2.26	5.07	1.60
	Sugarcane	Roi Et	1.63	1.57	1.75	1.60	1.71	5.50	6.60	4.89	7.74	11.05
	Rice paddy	Roi Et	1.62	1.83	1.70	1.77	1.87	1.62	1.83	1.70	1.77	1.87
Kosum Phisai	Forest	Khorat	1.44	1.34	1.40	1.45	1.47	0.96	1.82	0.96	1.92	2.78
	Cassava	Khorat	1.49	1.52	1.49	1.51	1.65	4.64	5.26	5.40	7.68	15.98
	Sugarcane	Khorat	1.44	1.49	1.56	1.58	1.75	4.13	5.74	6.10	9.40	13.73
	Rice paddy	Khorat	1.62	1.67	1.60	1.61	1.63	3.95	7.57	8.87	11.17	21.16
Kut Rang	Forest	Nam Phong	1.59	1.51	1.51	1.51	1.51	0.66	0.83	0.87	0.99	0.85
	Cassava	Nam Phong	1.50	1.65	1.59	1.74	1.73	4.01	7.14	7.56	12.96	16.33
	Sugarcane	Ubon	1.51	1.54	1.61	1.49	1.63	0.85	2.07	10.91	6.10	12.09
	Rice paddy	Satuk	1.71	1.59	1.56	1.87	1.63	4.85	2.21	14.39	13.89	12.13
Borabue	Forest	Khorat	1.61	1.50	1.43	1.54	1.58	1.38	1.43	2.15	7.97	7.83
	Cassava	Khorat	1.58	1.78	1.60	1.53	1.56	1.37	6.35	6.72	7.33	7.11
	Sugarcane	Roi Et	1.55	1.58	1.55	1.95	1.84	4.73	3.47	3.54	11.58	12.27
	Rice paddy	Roi Et	1.56	1.60	1.58	1.63	1.72	1.17	1.97	4.64	9.42	14.23
Wapi Pathum	Forest	Ubon	1.64	1.64	1.65	1.58	1.51	2.26	5.07	5.47	0.47	9.84
	Cassava	Ubon	1.54	1.57	1.60	1.70	1.72	5.06	3.71	13.07	18.33	18.80
	Sugarcane	Ubon	1.43	1.47	1.50	1.56	1.61	7.12	8.02	9.29	11.15	14.52
	Rice paddy	Ubon	1.57	1.64	1.60	1.66	1.78	2.23	7.07	16.36	19.66	17.46

Table 3. ANOVA results for soil phosphorus in different soil depths from four land uses and six locations

	df	p-value
Location	5	0.00
Land use	3	0.00
Location x Land use	15	0.00
Location	5	0.00
Land use	3	0.00
Soil depth ^{1/}	1	0.00
Land use x Soil depth ^{1/}	3	0.00
Location x Soil depth ^{1/}	5	0.00
Location x Land use	15	0.00
Location x Land use x Soil depth ^{1/}	15	0.00
Location	5	0.00
Land use	3	0.00
Soil depth ^{2/}	4	0.00
Land use x Soil depth ^{2/}	19	0.00
Location x Soil depth ^{2/}	29	0.00
Location x Land use	23	0.00
Location x Land use x Soil depth ^{2/}	119	0.00

^{1/}: two soil depths, including topsoil (0–20 cm), subsoil (20–100 cm).

^{2/}: five soil depths, including 0–20, 20–40, 40–60, 60–80, 80–100 cm.

land uses, whereas Roi Et soil series covered sugarcane and paddy land uses.

ANOVA for Phosphorus Stocks in Different Soil Depths Under Four Land Uses and Six Locations

A combined analysis is shown in Table 3. Means of available P content from different soil depths (one; 0–100 cm), two; 0–20, 20–100

cm), five; 0–20, 20–40, 40–60, 60–80, 80–100 cm), four land uses and six locations as well as their interactions were significantly different ($p = 0.00$).

Distribution of Phosphorus in Soil Profile

Stocks of available P in whole soil profile (0–100 cm), top–subsoil (0–20, 20–100 cm) and five soil depths (0–20, 20–40, 40–60, 60–80, 80–

Table 4. Means for phosphorus stock (kg ha⁻¹) in soil profiles averaged from four land use types and six locations

Land use types	Soil depths		
	1 ¹	2 ²	5 ³
Forest	67.7C (–)	33.9C (–)	13.5C (–)
Cassava	147.8B (+118%)	73.8B (+118%)	29.6B (+119%)
Sugarcane	234.0A (+245%)	117.0A (+245%)	46.8A (+247%)
Rice paddy	63.2C (–7%)	31.6C (–7%)	12.6C (–7%)
CV (%) (Location x Replication x Land use x Soil depth)	8.62	10.91	17.67
F-test	**	**	**

Means in a same column followed by the different lowercase letters are significantly different by LSD ($p < 0.01$, **)

¹: one soil depth, 0–100 cm

²: two soil depths, including topsoil (0–20 cm), subsoil (20–100 cm)

³: five soil depths, including 0–20, 20–40, 40–60, 60–80, 80–100 cm

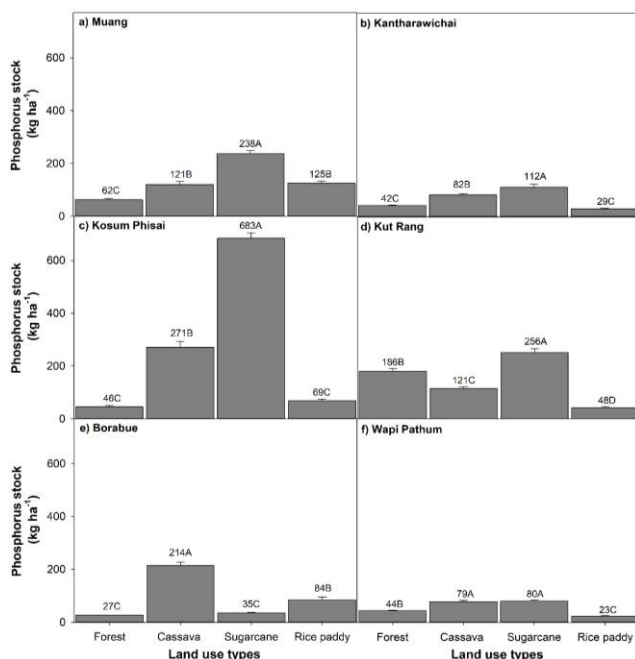


Figure 3. Land-use changes affecting phosphorus stocks in whole soil profile (0-100 cm) in six districts. Similar uppercase letters on top of bar graphs indicate no significant differences ($p > 0.05$) as calculated by the least significant difference (LSD). Error bars represent standard error of the mean

100 cm) from six locations were significantly highest in sugarcane soil followed by cassava, forest and paddy soils, respectively ($p < 0.01$; Table 4).

For distribution of P in whole soil profiles (0-100 cm), available P stocks were highest in sugarcane soils in all districts, with the exception of the Borabue, which had low P stock (Figure 3). Meanwhile, the lowest P

stocks in forest soils were found in the Muang, Kosum Phisai and Borabue (Figures 3(a), 3(c), 3(e)) and in paddy soils in Kantharawichai, Kut Rang and Wapi Pathum (Figures 3(b), 3(d), 3(f)). When comparing between lowland and upland soils, upland soils (sugarcane and cassava) had higher P stocks than in the lowland soil (rice paddy).

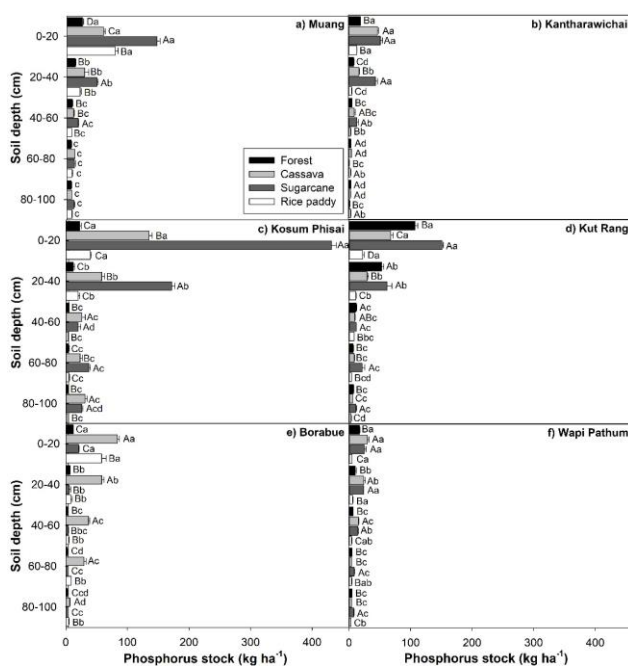


Figure 4. Land-use changes affecting distribution of phosphorus in soil profile in six districts. Similar uppercase letters on top of bar graphs representing different phosphorus stocks among soil depths in each land use, indicate no significant differences ($p > 0.05$) as calculated by the least significant difference (LSD). Similar lowercase letters on top of graphs representing different phosphorus stocks among soil depths in each land use, indicate no significant differences ($p > 0.05$) as calculated by the least significant difference (LSD). Error bars represent standard error of the mean

Distribution of P in five soil depths (0-20, 20-40, 40-60, 60-80, 80-100 cm) is shown in Figure 4. In all districts, topsoils (0-20 cm) had higher amounts of P stocks than in subsoils (20-100 cm) (Figures 4(a)-4(f)). In the Muang, Kantharawichai, Kosum Phisai and Kut Rang, sugarcane top and subsoils yielded higher P stocks than the other land uses (Figures 4(a)-(4d)). Whereas in the Borabue and Wapi Pathum, P stocks in the cassava top and subsoil were higher than in the other land uses (Figures 4(e)-4(f)).

Stocks of Phosphorus in Topsoil and Subsoil

There were different patterns of P stock in topsoil and subsoil among the land uses in each district (Figure 5). Phosphorus stocks were significantly higher in topsoils than in subsoils under forest (Kut Rang district), cassava (Kantharawichai and Kut Rang districts),

sugarcane (Muang, Kosum Phisai and Kut Rang districts), and rice paddy (Muang district) (Figures 5(a)-5(e)). Meanwhile, an opposite pattern was found in forest (Muang, Borabue and Wapi Pathum districts), cassava (Borabue and Wapi Pathum districts), and sugarcane as well as rice paddy (Wapi Pathum district) (Figures 5(a), 5(e), 5(f)). Sugarcane soil had higher P stock in both topsoil and subsoil in all districts (Figures 5(a)-5(d), 5(f)), with the exception of the Borabue district (Figure 5(e)). For proportional P stock in topsoil and subsoil (Figure 6), it has similar pattern with the amount of P stock in the Figure 5.

Discussion

When considering P stock in each land use throughout soil profiles (0-100 cm), we found

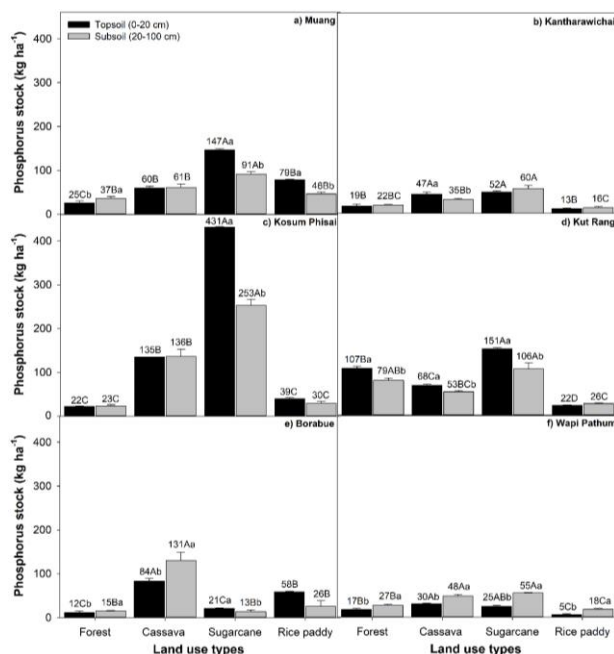


Figure 5. Land-use changes affecting phosphorus stocks (kg ha^{-1}) in topsoil (0-20 cm) and subsoil (20-100 cm) in six districts. Similar uppercase letters on top of bar graphs, comparing phosphorus stocks among the land uses in top and subsoil, indicate no significant differences ($p>0.05$) as calculated by the least significant difference (LSD). Similar lowercase letters on top of bar graphs, comparing phosphorus stocks between top and subsoil in each land use, indicate no significant differences ($p>0.05$) as calculated by the least significant difference (LSD). Error bars represent standard error of the mean

that upland soil (i.e., sugarcane and cassava land uses) had larger amounts of P stocks than in paddy and forest soils. This is due to the fact that most of upland crops in this area have been produced for commercial purposes. Thus, higher rates of fertilizer input have been required. Our findings are similar to a study done in a different site but in the same province by Kunlanit (2018), who pointed out that cassava soil had higher available P stock than paddy and forest soils. In addition, many studies also found similar results to the current study (Kaweewong *et al.*, 2013; Saenya *et al.*, 2015; Groppo *et al.*, 2015; Kunlanit, 2018). They suggested that P fertilizer application to crops enhanced P levels in these arable soils. In the current study, there was a wide range of P stock in sugarcane (35 to 683 kg ha^{-1}) and cassava (79 to 271 kg ha^{-1}) soil profiles across the study locations. We speculated that

proportion of P stock remaining in soil might depend upon amount of chemical fertilizer applied and remaining sugarcane and cassava residues on soil surfaces after harvesting in each study location. We also found that cattle manure incorporation to soil prior to sugarcane and cassava cultivations could not enhance P stock as seen by low P stock in sugarcane and cassava soils in Wapi Pathum with cattle manure input, while P stocks were high in sugarcane and cassava soils in Kosum Phisai location without cattle manure input. This is because of cattle manure containing low amount of P ($7\text{--}32 \text{ mg kg}^{-1}$) (Li *et al.*, 2014) in comparison to chemical fertilizer. For paddy land, low amount of chemical fertilizer input in rice paddy during growing season, and removal of P with rice harvested could contribute to low amount of P stock left in the paddy soil, as compared to the upland soils in

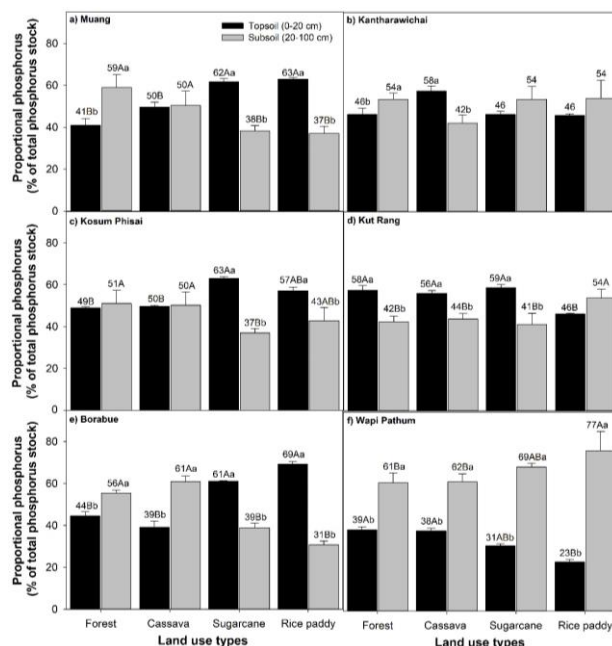


Figure 6. Land-use changes affecting proportional phosphorus (% of total phosphorus stock) in topsoil (0-20 cm) and subsoil (20-100 cm) in six districts. Similar uppercase letters on top of bar graphs, comparing phosphorus stocks among the land uses in top and subsoil, indicate no significant differences ($p>0.05$) as calculated by the least significant difference (LSD). Similar lowercase letters on top of bar graphs, comparing phosphorus stocks between top and subsoil in each land use, indicate no significant differences ($p>0.05$) as calculated by the least significant difference (LSD). Error bars represent standard error of the mean

this study. Our results are similar to the findings of Kunlanit (2018), who found that P stock in paddy soil was low. In a close system (forest), no chemical fertilizer added to the forest soil resulted in lower amount of P stocks than agricultural soil, although litterfall in forest land had not been removed from the soil surfaces. Likewise, a study in South Western Uganda by Majaliwa *et al.* (2010) found that natural forest soil had lower available P stock than arable soils (e.g., tea and eucalyptus).

Our study showed that sugarcane and cassava had higher P stock in both topsoil and subsoil than in paddy and forest soils. For the topsoil, high amounts of chemical fertilizer are incorporated to soil surface (root zone) during growing season is a possible reason to enhance P stock in topsoil of both upland crops. The current findings are similar to the results by Jobbagy and Jackson (2001), Groppo *et al.*

(2015) and van der Wal *et al.* (2017), who all found that topsoils had higher available P stock than subsoils. In addition, a few studies in sand to clay textures by Wongkhiew *et al.* (2017) and in a sandy clay loam soil by Phimsirikul and Matoh (2003) showed that sugarcane topsoil had higher available P contents than in subsoil. For cassava soil, a few investigations in sandy soil in Thailand by Amonpon *et al.* (2013) and Phimsirikul and Matoh (2003) found that available P content in cassava topsoil was higher than in subsoil (20-50 cm). For subsoil, available P stocks in upland subsoils (i.e., sugarcane and cassava) of the current study were high. We speculate that agricultural practices, such as high amount of chemical fertilizer input and deep plowing of the soils prior to crop growing might enhance movement of P from topsoils to accumulate in subsoils especially during a rainy season. This

is due to the fact that most of soils in the current study had high sand contents (73–91%) as sandy soil has low affinity for adsorption (Strawn *et al.*, 2015). This might lead to low P absorption onto mineral surfaces of the sandy soil. Thus, P is preferentially leached from topsoil and accumulated at subsoil layer with higher clay content.

In paddy soil, we have speculated that agricultural practices during rice paddy growing affect patterns of P accumulation in topsoil and subsoil. In sandy loam and sandy clay loam soils from Muang, Kosum Phisai and Borabue districts, topsoils tended to have higher P stock than in the subsoils. Our results are similar to that of a study done in sandy clay loam soil of Northern Thailand by Phimsirikul and Matoh (2003), who reported that P stock in paddy topsoil was slightly higher than in subsoil (20–40 cm). Additionally in Thailand, Phimsirikul and Matoh (2003) also found that available P stock in paddy topsoils of Banglen (Typic Haplaquills) and Chachoengsao (Typic Thropaquepts) soil series were higher than in subsoils. In Ultisol soil of Southwest China, Yang *et al.* (2014) found that paddy topsoil had larger amounts of total P than in subsoil (20–100 cm). However, in Kantharawichai, Kut Rang and Wapi Phathum districts of the current study, the paddy topsoils yielded lower P stocks than in the subsoils. Likewise, Chen *et al.* (2017) also found that P contents in topsoils of cereal fields were lower than in the subsoils in all 11 studied sites.

Phosphorus stock in forest topsoil of Kut Rang district was higher than in subsoil. That is, decomposition of litterfall and fine root on soil surfaces enhances soil organic matter (SOM) in forest soil (Guimaraes *et al.*, 2013) as SOM is a source of organic P in soil (Stevenson, 1994). A study in Northeast Thailand by Kunlanit *et al.* (2019), who also found that SOM in Deciduous dipterocarp forest topsoil was higher than subsoil. Similarly, Adugna and Abegaz (2011) found that P content in forest topsoil was higher than in a subsoil. In addition, Brams (1973) reported that tropical forest topsoil (0–15 cm) had higher P content than in a subsoil (32–60

cm). In beech forest in Central Europe, Lang *et al.* (2017) also found total P stock in a topsoil was higher than in a subsoil. Fang *et al.* (2015) pointed out that broad-leaved forest topsoil (0–15 cm) had higher amount of P stock than in a subsoil (15–45 cm).

We found that P stock was higher in the forest subsoil than in the topsoil in five districts. It indicates that leaching of dissolved organic P (DOP) from topsoil to subsoil can enhance P accumulation in the subsoil (Reid *et al.*, 2018) of forest (close system). Leaching of SOM or DOP is high in a sandy soil with low affinity for adsorption (Stevenson, 1994). Most of soils in the current study are sandy soils as well. Our findings are similar to the results by Sugihara *et al.* (2017) found that P stock in forest subsoil was slightly higher than in a topsoil. In China, Fang *et al.* (2015) reported that coniferous forest subsoil (15–45 cm) had higher P stock than in a topsoil (0–15 cm).

The results in this study showed that fertilizer management can restore P in upland soil after the conversion of forest land to upland crop. To maintain P in paddy soil for enhancing rice yield, fertilizer management and minimizing stubble burning are needed.

Conclusions

Our study found that topsoil (0–20 cm) in all land uses from six locations tended to higher P stock than in each of the five layers of subsoils. Agricultural practices, such as high rate of P fertilizer application, can enhance P stocks in soils of upland crops (i.e., sugarcane and cassava), compared to paddy and forest soils. Additionally, deep plowing in the upland soils before crop plantation can enhance P leaching from the topsoil to the subsoil, as seen by the higher amount of P accumulation in the upland subsoils. This study suggests that similar land use with different agricultural practices could lead to different patterns of P distribution in both topsoil and subsoil. To maintain P in agricultural soil, fertilizer management for crop cultivation is needed.

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