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Soil Spatial Variation in a Sloping Mango Orchard of Northern Peninsular Malaysia

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ABSTRACT

The present study investigated the spatial variation of the physico-chemical characteristics of lateritic soil profiles (up to 60 cm in depth) in a sloping mango orchard (1 ha; slope gradient = 6 %) in North Peninsular Malaysia. The study revealed that horizontal variation for the exchangeable Al and Mg, and the particle size fractions in the topmost soil layer (0–15 cm) within the orchard was higher than their vertical variation within the soil profile, and that, in contrast, the opposite trend was found for the total N, cation exchange capacity, and base saturation. Furthermore, preferential accumulation of soil organic matter and nutrients such as total N and available P were found at the lower (LS) and/or middle (MS) slope positions than the upper (US) one, while the lower clay content with the higher clay activity index was observed at LS compared to MS and US. These results suggest that these variations occur by the scattered accumulation of fertilizer-derived nutrients (i.e. N, P, K, and Mg) in the surface soil layers and the translocation of the surface litter, soil and nutrients towards the downslope in addition to enhanced eluviation process with the residual of clays at the downslope in the sloping orchard.

Key words: **Lateritic soil, *Mangifera indica* L., slope position, spatial variation, ultisols**

INTRODUCTION

Northern Peninsular Malaysia is one of the most productive areas of mango (*Mangifera indica* L.) cultivation in this country because the climate in this region, i.e. tropical monsoon climate with a short dry spell (January–March), is highly suitable to induce flowering and fruit development (DOA 2009). Mango is a tree (perennial) crop which has a vigorous rooting system in the soil up to approximately 0.5 m in depth (Bojappa and Singh 1975) and may have the main root reaching more than 1 m in depth (Lehmann 2003); hence, mango is often planted in lateritic soil landscapes because it is efficient in absorption of nutrients and water from deep soil layers and survives well at low-fertility soils and during dry periods (Ganeshamurthy and Reddy 2015). However, there is a certain gap between the actual and potential yields of mango in the lateritic soil areas (de Bie 2004; Zhang *et al*. 2019), and soil fertility management has been identified as a key practice in filling this gap (DOA 2009). Hence, further information on soil properties in mango orchards of the study region is essential to formulate a strategy for enhancing sustainable mango cultivation.

From this viewpoint, our previous study (Shahidin *et al*. 2018) examined the spatial variation and distribution pattern of the fertility characteristics of the topsoil in a mango orchard in this region and found certain variations (coefficient of variation [CV] = 13.7–45.1 %; n = 50) of most soil properties such as organic C, total N, available P, exchangeable bases, exchange acidity and effective cation exchange capacity (ECEC) within a small steep field (approximately 1 ha; slope = 6 %). However, soil properties can also vary vertically within a pedon on sloping lands. In an extreme case, for instance, Kinoshita *et al*. (2021) reported that soil properties vary to a degree in which soil great group differs within a short distance in a small sloping crop field (area = 0.2 ha, slope = 7 %) of Sabah, Malaysia. Currently there is a dearth of research that takes into account the root structure of the mango tree and the vertical variation of soil profiles in sloping mango orchards. Such information is important to improve mango production in lateritic soil landscapes. Therefore, the objective of this study was to examine spatial variation of the physico-chemical properties of lateritic soil profiles in a sloping mango orchard in Northern Peninsular Malaysia with an emphasis on the changes in soil characteristics relative to the slope position.

MATERIALS AND METHODS

Study Site

A field survey was conducted at the experimental farm of Universiti Teknologi MARA (06°27′15″N; 100°17′01″E), which is located in the middle of Perlis, Malaysia. The study area has a tropical monsoon climate (*Am* in the Köppen-Geiger classification system) with a mean air temperature of about 27°C and average annual precipitation of approximately 1,900 mm. The landform of the study area is predominated by an undulating topography. The soil at the experimental farm is largely classified as Typic Paleudults in the U.S. Soil Taxonomy and is locally referred to as the Terap Series (Satar *et al*. 2005).

Survey Site

A mango orchard (1 ha) situated on sloping land (mean gradient = 6 %) was selected for this study. Here, the mango trees (cv. Harumanis or MA 128; 5 years old as of September 2014) were planted at a density of 123 trees ha^{-1} in a square (9 m × 9 m) planting system. The orchard has been fertilized following the recommendation of the Malaysian Department of Agriculture (DOA 2009) from the time the orchard was established in September 2009. Briefly, a compound fertilizer (12-12-17-2-8S-TE: Nitrophoska® Blue TE, Behn Meyer Agricare, Selangor, Malaysia), which contains 2 % MgO, 8 % S, 0.02 % B, and 0.01 % Zn (w/w) in addition to 12 % N, 12 % P_2O_5, and 17 % K_2O, was applied at 3 kg per tree each year in two split applications (usually in July and October). In other words, the plot had received fertilizer equivalent to 48 kg N ha^{-1}, 48 kg P_2O_5 ha^{-1}, and 68 kg K_2O ha^{-1} every year until 2013. The application rate was increased up to 3.5 kg $tree^{-1}$ $year^{-1}$ (equivalent to 56 kg N ha^{-1}, 56 kg P_2O_5 ha^{-1}, and 79 kg K_2O ha^{-1}) in 2014. The fertilizer was applied on the topmost soil layer (0–15 cm) by the pocket placement method (i.e. 4 pockets per tree; 2 m away from the tree base).

The mango trees in the orchard were subjected to structural pruning three times every year. In the case of 2014, the first pruning was done after the harvest of all fruits to reshape the trees (in June), the second was performed to remove the excessive, infected, and dead branches (in September), and the third pruning was committed to removing all suckers from the main structural branches (in November) two weeks before the fertilizer application. The control of weeds at the study site was optimized by the combined use of chemical and physical methods:

the application of a non-selective herbicide (i.e. glufosinate-ammonium) using a boom sprayer in addition to the mechanical clearing by a rotor slasher attached to a tractor once every two or three months. Pruned trees were removed from the orchard, while cleared weeds were left in the orchard.

Soil Sampling

Soil sampling was conducted at the mango orchard in July 2014. Nine soil pits (75 cm length × 100 cm width × 90 cm depth) were dug within this plot (Figure 1). These soil pits were categorized into three groups due to the slope positions at the orchard: lower (LS), middle (MS), and upper (US) positions. These soil pits were prepared approximately 2 m away from the main trunk in the approximate centre between the mango tree base and the service path. Soil samples were taken from four different depths, i.e. 0–15, 15–30, 30–45, and 45–60 cm, respectively. The soil samples were dried in an oven at 60°C for 48 h, gently ground, and passed through a mesh sieve (ϕ = 2.0 mm) before the laboratory analysis.

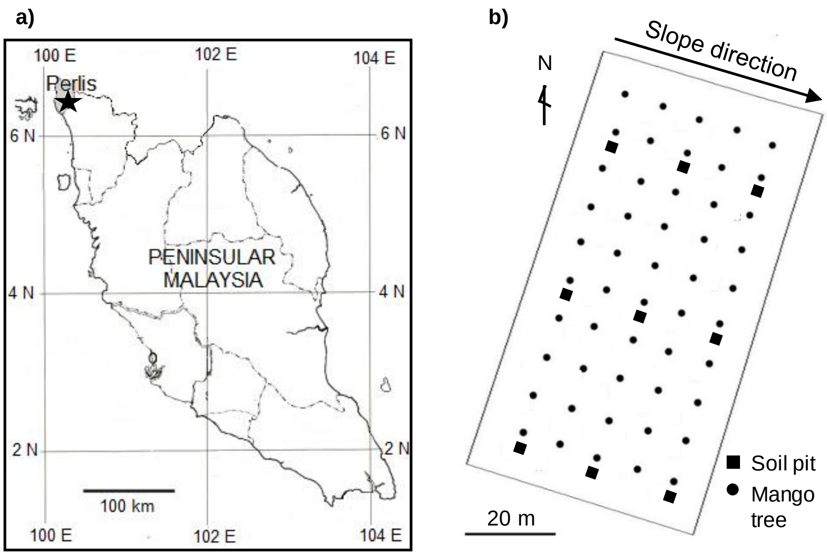

Figure 1. (a) Location of the study site in Peninsular Malaysia and (b) schematic layout of the sampling locations at the study site

Laboratory Analyses

The physico-chemical properties of the soil samples were analysed according to the standard methods in the field of soil science. Briefly, soil pH was measured in distilled water in a solid:liquid ratio of 1:2.5 (w/v). Total C and N were simultaneously determined by an elemental analyser (TruMac CNS-2000, LECO, St. Joseph). Here, all C in the samples was considered to exist in organic forms as soil pH in these samples was lower than 6.5 (van Reeuwijk 2002). Available P was extracted with Bray No. 2 extractant, consisting of 0.03 mol L^{-1} ammonium fluoride and 0.1 mol L^{-1} hydrochloric acid (Bray and Kurtz 1945), and its concentration was determined by the flow injection analyser (Lachat QuickChem 8000 series FIA+, Zellweger Analytics, Milwaukee). Exchangeable bases (K, Ca, and Mg) and Al were extracted with 1 mol L^{-1} ammonium acetate (pH = 7) and 1 mol L^{-1} potassium chloride, respectively. The concentrations of the bases and Al in the extracts were subsequently determined by atomic absorption spectrometry (AAnalyst 400, Perkin Elmer, Norwalk) and inductively coupled plasma optical emission spectrometry (Optima 8300, Perkin Elmer, Norwalk, CT), respectively. Cation exchange capacity (CEC) was measured by the Schollenberger method (Schollenberger and Simon 1945). Base and Al saturations were calculated as the occupational percentage of the sum of the exchangeable bases and the Al to the CEC, respectively. Soil particle distribution was measured by the pipette method (Gee and Bauder 1986). Soil textural class was determined according to the USDA's soil textural triangle (Murano *et al*. 2015). The clay activity index was computed through the division of CEC by the clay content.

Statistical Analyses

To examine soil variability, the horizontal and vertical variations were evaluated by calculating the coefficient of variation (CV) in a horizontal direction within the orchard and in a vertical variation within the soil profile, respectively. For the former, CV was calculated using the soil data (n = 9) at the topmost layer. Meanwhile, for the latter, CV was acquired as the mean of nine CVs calculated from soil data of four soil layers comprising the soil profile. One-way analysis of variance (ANOVA) was performed using the slope position as the fixed factor, assuming the Gaussian distribution of the populations and the homoscedasticity of their errors. The mean separation was subsequently made at a significance level of $p < 0.05$ by Tukey's test. In addition, Pearson's correlation coefficients were calculated among the examined soil variables. All statistical analyses were done using statistical software (SPSS 23, IBM, Chicago, IL).

RESULTS AND DISCUSSION

General Fertility Characteristics and Pedogenic Features

Table 1 shows the physicochemical properties of the soils at the study site. Referring to the soil fertility ratings by Nyi *et al*. (2017), the soils in the topmost layer (0–15 cm) had a strongly acidic reaction (pH < 5.0), medium levels of organic C (15–29 g kg^{-1}) and available P (10–15 mg kg^{-1}), and low levels of total N (< 1.4 g kg^{-1}), exchangeable K (< 0.23 $cmol_c$ kg^{-1}), and CEC (< 10 $cmol_c$ kg^{-1}). These soils also had a relatively high Al saturation (> 11 %) and low base saturation (< 50 %), corresponding to low soil pH and high exchangeable Al. The exchangeable Al concentration in the studied soil ranged from moderate (0.5–1.0 $cmol_c$ kg^{-1}) to high levels (1.0–2.5 $cmol_c$ kg^{-1}) and it was observed that there would be an Al toxicity risk because Al saturation (16.2 ± 6.2 %) was higher than 11 % (Nyi *et al*. 2017). The clay activity index was low, i.e. CEC < 16 $cmol_c$ kg^{-1} clay (Kimble *et al*. 1993) which indicates that clay minerals in these soils are probably dominated by low-activity clays such as kaolinite and gibbsite (Zhang *et al*. 2004a). All these soil parameters represent the general characteristics of lateritic soils, which have been documented in literature (Sehgal 1998). Moreover, soil pH, total N, and exchangeable Ca and Mg were found lower than the optimal ranges for mango cultivation: pH = 5.5–6.5 (DOA 2009); total N = 3–6 g kg^{-1}; Ca = 3.0–5.0 $cmol_c$ kg^{-1}; Mg = 0.75–1.25 $cmol_c$ kg^{-1}; while exchangeable K marginally fell into the recommended range: 0.25–0.38 cmolc kg^{-1} (Poffley and Owens 2005). The optimal range of available (Bray 1) P for mango cultivation has not been documented in the literature. Although none of the apparent visible symptoms of these nutrient disorders were observed in the mango trees during the field survey (Shahidin *et al*. 2018), the analysis of the leaf nutrients revealed luxury N but deficient Ca status of the mango trees at the study site (Shahidin *et al*. 2022). The particle size distribution of the soils at the study site consisted of more than 50 % clay, less than 20 % of silt, and about 30 % sand and thus soil texture was classified as "clay". The clay texture has been observed in many lateritic soils, depending mainly on parent materials (Zhang *et al*. 2004b; Ko 2014).

TABLE 1
General fertility characteristics of the topmost soil layer (0–15 cm) at the study site

Property	Unit	Mean (SD)
pH	—	4.4 (0.7)
Exchangeable Al	$cmol_c\ kg^{-1}$	1.3 (0.5)
Al saturation	%	16.2 (6.2)
Organic C	$g\ kg^{-1}$	16.9 (6.1)
Total N	$g\ kg^{-1}$	1.24 (0.44)
C/N ratio	—	13.0 (2.2)
Available P	$mg\ kg^{-1}$	11.9 (10.0)
Exchangeable K	$cmol_c\ kg^{-1}$	0.29 (0.15)
Exchangeable Ca	$cmol_c\ kg^{-1}$	1.5 (0.3)
Exchangeable Mg	$cmol_c\ kg^{-1}$	0.6 (0.3)
CEC	$cmol_c\ kg^{-1}$	7.9 (0.3)
Base saturation	%	31.0 (3.1)
Clay	%	52.5 (7.5)
Silt	%	17.2 (3.6)
Sand	%	30.3 (4.3)
Clay activity	$cmol_c\ kg^{-1}$	15.4 (2.4)

The studied soils also had some pedogenic features which are commonly investigated in the lateritic soils (Sehgal 1998), including the yellowish red matrix colour (5YR 5/8) and the presence of clay skins (cutans) on the ped surface of the subsoil layers. These are visual signs of the predominant presence of iron hydr(oxy)oxides, e.g. goethite and hematite (Abe and Wakatsuki 2010) and the translocation of clay from the upper to the lower horizons within the soil profile (Abe *et al.* 2009). The latter was in accordance with the increase in the clay content with increasing soil depth (> 20 %, w/w) within the soil profile which denotes the formation of the argillic (clay-illuviated) horizon in these soil profiles (Zhang *et al*. 2004b).

Soil Variability: The Horizontal vs. Vertical Variations

The horizontal variation of the examined soil variables at the topmost layer within the study site and their vertical variation within the soil profile are comparatively shown in *Figure 2.* Among the soil layers within the soil profile, the horizontal variation of all soil variables at the topmost layer exhibited the highest CV, except for the exchangeable Ca and Mg. These bases showed the highest CV in the second-top layer within the soil profile (see error bars in *Figure 3).* Both horizontal and vertical variations were found to be relatively low (CV < 25 %) for the pH, C/N ratio, exchangeable Ca, CEC, particle size distribution (i.e. clay, silt, and sand), and clay activity index. Most of these soil variables are associated with pedogenesis and their relatively low spatial variations represent relatively monotonous physicochemical characteristics at the study site which has formed from homogenous parent material under a long-lasting laterization process in this region. On the other hand, the remaining soil variables i.e. exchangeable Al, Al saturation, organic C, total N, available P, exchangeable Mg and K, and base saturation showed intermediate (CV = 25–75 %) or relatively high (CV > 75%) variation.

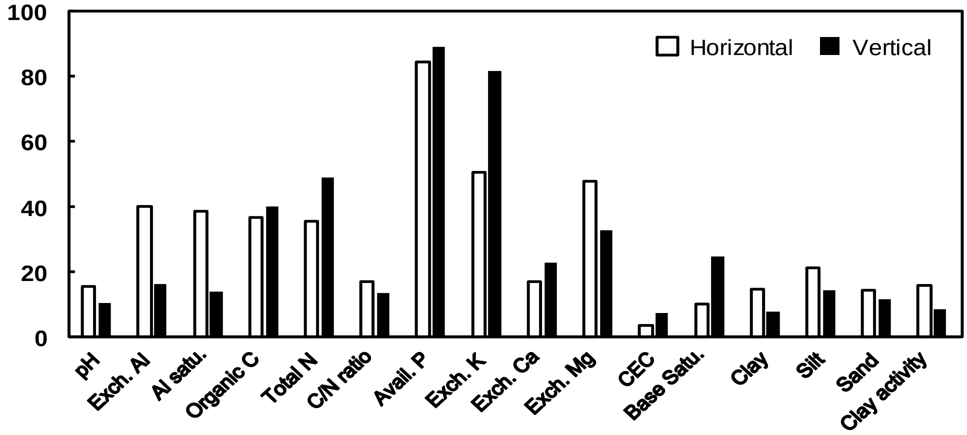

Figure 2. Comparison of the coefficients of variation (%) between the horizontal and vertical variations for each of the soil variables at the study site

Note: Horizontal variation is calculated based on the mean and standard deviation of the topmost soil layers (n = 9), while vertical variation is presented as the mean of the coefficients of variation (n = 9) calculated from the variation among soil layers (n = 4) within each soil profile.

Moreover, the horizontal variation of some of these variables such as total N, exchangeable K and Ca, CEC, and base saturation was lower than the vertical variation. This was in contrast to pH, exchangeable Al and Mg, Al saturation, clay, silt, and clay activity index which showed a higher horizontal variation than the vertical variation. The variations of these variables reflect the anthropogenic impacts which are largely derived from agricultural practices. In particular, it should be noted that available P, exchangeable K and Mg, and total N were regarded as the top four variables which had the highest CV either or both vertical and horizontal variations and that all these variables are related to the nutrients included in inorganic fertilizer which has been used at the study site. The most typical case is seen for available P because it exhibited the highest variations among the soil variables investigated in this study (Shahidin *et al*. 2018) as P is less mobile in soil than the other nutrients due to the fixation of fertilizer-derived P with iron and/or manganese in acidic soils (Brady and Weil 2008). However, this is contradictory to the conclusion of our previous study (Shahidin *et al*. 2018) which suggested that spatial characteristics of these four variables in the topmost soil layer may have formed under the stronger influence of intrinsic factors such as soil texture and mineralogy rather than extrinsic factors such as agronomic practices (e.g. the application of chemical fertilizers), based on the strong spatial dependency judged by the nugget-to-sill (N/S) ratio < 0.25 in the constructed semi-variograms. This contradiction indicates a possible misinterpretation of geo-statistical results in our previous study (Shahidin *et al*. 2018) and supports alarming concerns on the N/S ratio by Oliver and Webster (2014) who pointed out that the use of the N/S ratio of the empirical variogram as a measure of spatial dependence has flaws because (i) the N/S ratio is affected by measurement error as well as error arising from the uncontrolled fitting over distances shorter than the shortest lag and the choice of model;

(ii) the fitted sill is an uncertain estimate of the sill of the underlying process; and (iii) the ratio takes no account of the correlation range, which can lead to a sensible inference.

Soil Profile Characteristics Relative to the Slope Position

Soil pH, Exchangeable Al, and Al Saturation

The profile distributions of the pH value, exchangeable Al concentration, and Al saturation are shown according to the slope position in *Figure 3.* At the topmost soil layer, a higher pH value was found at LS than those at US and MS without any significant difference. Irrespective of the slope position, the soil pH value decreased as the soil depth increased, except for the second-top layer (15–30 cm) at MS and US which had a slightly higher pH value compared to the overlying topmost layer and the underlying third- (30–45 cm) and fourth-top (45–60 cm) layers, respectively. The exchangeable Al and Al saturation exhibited an opposite trend to the soil pH: both of them were lower at US than MS and LS throughout the soil profile without any significant differences among the slope positions. Furthermore, the exchangeable Al and Al saturation were lowest at the topmost soil layer and slightly increased with increasing soil depth up to the third-top layer (30–45 cm) within the soil profile. The relationships of pH with available Al and Al saturation adequately reflected the negative correlations between the pH and the exchangeable Al as well as between the pH and the Al saturation (Table 2), which is seen very commonly in acidic soils as the Al in the soil becomes more soluble with the decline in the pH (Brady and Weil 2008).

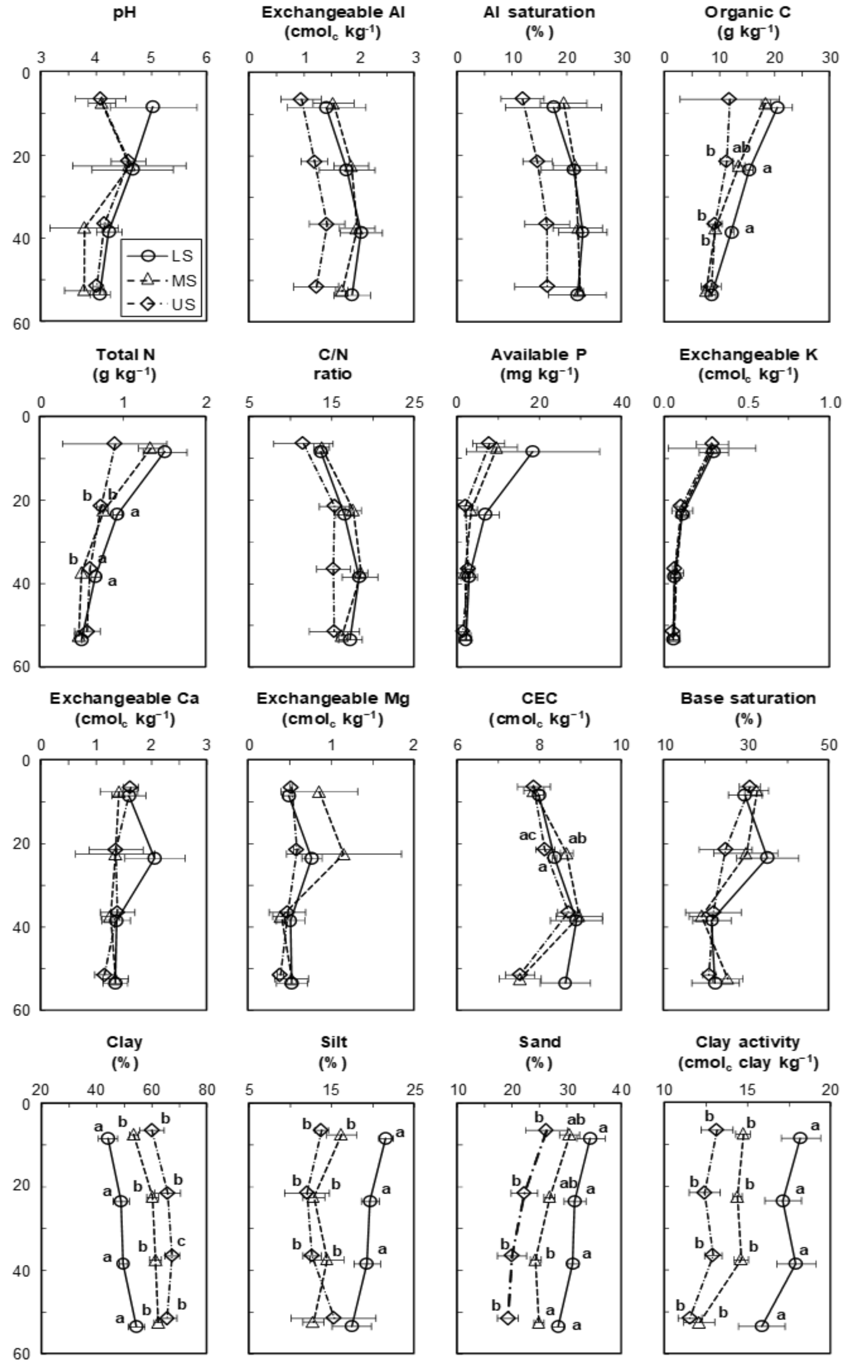

Figure 3. Comparison of soil physico-chemical properties in the soil profile among the different slope positions at the study site

Note: Different letters denote significant differences among slope positions at each soil layer. Error bars indicate standard deviation

TABLE 2

Pearson's correlation coefficients of soil variables examined in this study (n = 36)

	pH	Exch. Al	Al satu.	Org. C	Tot. N	C/N ratio	Avail. P	Exch. K	Exch. Ca	Exch. Mg	CEC	Base satu.	Clay	Silt	Sand
Exch. Al	-.319	1													
Al satu.	-.350*	.969***	1												
Org. C	.364*	-.163	-.154	1											
Tot. N	.290	-.262	-.220	.958***	1										
C/N ratio	-.036	.316	.208	-.084	-.338*	1									
Avail. P	.489**	-.270	-.237	.567***	.597***	-.278	1								
Exch. K	.252	-.402*	-.360*	.614***	.712***	-.462**	.698***	1							
Exch. Ca	.171	.167	.161	.288	.250	-.069	.160	.230	1						
Exch. Mg	.109	.186	.177	.237	.175	.009	.022	-.049	.038	1					
CEC	.058	.378*	.144	-.135	-.285	.498**	-.234	-.318	.031	.059	1				
Base satu.	.204	.024	.080	.517**	.518**	-.275	.351*	.460**	.753***	.554***	-.262	1			
Clay	-.348*	-.236	-.223	-.603***	-.533**	-.010	-.554***	-.350*	-.363*	-.106	-.060	-.384*	1		
Silt	.249	.227	.222	.421*	.398*	-.058	.417*	.226	.289	-.015	.033	.241	-.875***	1	
Sand	.361*	.214	.197	.635***	.542**	.056	.564***	.380*	.360*	.180	.067	.430**	-.938***	.653***	1
Clay act.	.373*	.343*	.232	.484**	.362*	.210	.420*	.171	.323	.085	.468**	.202	-.901***	.790***	.842***

Note: ***, **, and * denote significant levels at $p < 0.001$, $p < 0.01$, and $p < 0.05$, respectively

The higher soil pH values in the topmost soil layers than in the subsoil except for the second-top layers at US and MS, could reflect the additional buffering capacity accorded by soil organic matter content which was higher in the topmost soil layer than in the subsoil. In fact, organic C showed weak but positive correlations with the pH value (Table 2). Nevertheless, the lower pH value in some topmost soil layers than in the underlying second-top layers observed at US and MS, could be a result of soil acidification from the application of N fertilizers and subsequent leaching of N at the topmost layers as well as the accumulation of bases (Ca and/or Mg) at the second-top layers (Brady and Weil 2008).

Organic C, Total N, and Available P

Irrespective of the soil layer, organic C content was found in the order of US < MS < LS with some significant differences in particular at the subsoil layers among the slope positions (*Figure 3*). This organic C trend was followed by total N as indicated by the very strong positive correlation between these two parameters (Table 2). This is because most of them exist as components of soil organic matter in the non-calcareous soil (Brady and Weil 2008). Our results might reflect soil erosion and run-off which would carry the litter on the land surface from US to MS and LS since there was no clear difference in biomass production over the study site which was planted with one specific cultivar and managed uniformly in terms of agricultural practices. The translocation of the soil from US to MS and LS was also supported by the lower content of available P in US and MS in comparison to LS. The residual (mineral) P, which originates from the inorganic fertilizer, accumulates in the upper soil layers through fixation by Al dissolved under acidic conditions and can be transported from US and MS to LS by soil erosion and run-off. Soil organic matter also plays a role in providing nutrients for crops through microbial decomposition which subsequently contributes to bearing crop nutrients and reduces their loss through leaching. This is supported by the positive correlations of organic C with total N and available P (Table 2). Therefore, generally these parameters of soil fertility exhibit similar trends of distribution over one another within the study site irrespective of the slope position.

Accumulation of soil organic matter at the topmost soil layer could be derived from the organic inputs sourced from the plant residues after the seasonal pruning and the weeding. The study of Rodrigues *et al.* (2019) found that mango trees produced almost similar quantities of litter (7.1 Mg ha^{-1} yr^{-1}) to the adjacent open ombrophilous forest (9.0 Mg ha^{-1} yr^{-1}) on a Brazilian Oxisol and that the contribution of mango trees to the nutrient turnover to the soil via litter is similar to that of the forest. Irrespective of the slope position, the C/N ratio was found at the highest level in the topmost soil layer followed by a gradual decrease towards the deeper soil layers. This vertical trend of soil C/N ratio is often seen in agricultural fields and could reflect the organic input with the lower C/N ratio and the application of inorganic N in the surface soils. There was a little difference in the C/N ratio among the slope positions as represented by the low CV (*Figure 2*).

Exchangeable K, Ca, and Mg, CEC, and Base Saturation

Preferential accumulation of exchangeable K in the topmost soil layer as compared to the subsoil layers (*Figure 3*) could originate from K fertilizer applied at the topmost soil layer, whereas very low exchangeable K status in the subsoil layers would reflect its loss through the prolonged and intensive leaching (Sehgal, 1998). Similar to the relationship of the organic C with the total N and available P, the exchangeable K was positively correlated with organic C (Table 2). This is because soil organic matter, which accumulates in the topmost layer, enhances CEC and thus the retention of exchangeable bases (Brady and Weil 2008). Despite its large vertical variation, there was little and insignificant difference in the exchangeable K among the slope positions. This displays a similar trend as the other bases, i.e. Ca and Mg. These results suggest that the current scheme of soil fertility management using Mg-containing fertilizer is reasonable because of the deficient level of Mg found in the studied soils. However, an additional application of lime is highly recommended due to the deficient level of Ca and strong acidity in these soils. This was also supported by the deficit level of Ca (1.05 ± 0.43 %, n = 15; optimum range = 2.00–3.50 % (Malik 1989) in mango leaves found at the study site (Shahidin *et al*. 2022). The efficacy of trace elements (Zn and B) included in the compound fertilizer remains unclear and may need further research in future.

Unlike the other nutrients (N, P, and K) in the soil, which showed a downward decreasing trend in the soil profile in association with the organic C, the highest contents of both exchangeable Ca and Mg were found in the second-top layer (15–30 cm) within the soil profile. There were few differences in the exchangeable Ca and Mg among the slope positions, except for Ca in the second-top layer of LS and Mg in the topmost and second-top layers of MS which exhibited a slightly higher concentration than the other layers without significant differences. These distinctive distribution patterns of Ca and Mg within the soil profile could occur due to the uplift of the basic cations from the deeper soil layers through the uptake of these nutrients by mango trees and their returns to the upper soil layers via litter (Lehmann 2003). The results also suggest that mango roots help the accumulation of these bases leached from the overlying soil layer (0–15 cm in depth) which had received the compound fertilizer including Mg every year. The second-top soil layer (15–30 cm) is consistent with the active rooting zone of mango. Bojappa and Singh (1975) revealed that 75 % of the active mango roots are present in the upper 50 cm soil, and Pinto *et al*. (1996) reported that 77 % of the fine roots of mango trees are found in the subsurface soil layer (20–40 cm in depth).

Exchangeable K was positively correlated with pH value, while exchangeable Al was negatively correlated with exchangeable K (Table 2). Correspondingly, base saturation exhibited a strong negative correlation with exchangeable Al. These results suggest the reduced capacity to retain K due to its competition with Al for the cation exchange site on the colloid's surface in acidic soil (Brady and Weil 2008). In contrast, both exchangeable Ca and Mg were significantly correlated with neither the pH value nor the exchangeable Al, while the base saturation exhibited a strong negative correlation with exchangeable Al. These results suggest less susceptibility of bivalent Ca and Mg to soluble Al compared to monovalent K (Brady and Weil 2008)

Particle Size Distribution and Clay Activity Index

Particle size data (Figure 3) indicates that irrespective of the slope position, all soil layers constituting the soil profile had more than 40 % of clay and were categorized into the clay texture. The clay texture of the studied soils suggests their imperfectly drained characteristics after heavy and/or continual rains, although the mango trees can tolerate periodically flooded soils and generally poor soil drainage is not a problem (Crane *et al*. 2007). The monotonous soil texture found throughout the soil profile and over the slope positions suggest homogeneous parent material and a monotonous soil-forming process spread over the study site. This result is consistent with our field note: there was a great similarity in the soil profile description irrespective of the slope position (descriptions are not shown here).

Nevertheless, there were some significant differences in the particle size data among the slope positions: clay content was found in increasing order of US $\geq$ MS > LS, while the reverse order (i.e. LS > MS $\geq$ US) was observed for the contents of both sand and silt within the soil profile. In particular, differences in the content of clay, silt, and sand between LS and US were statistically significant in most soil layers, whereas those between MS and US were detected in a few soil layers only. The cause for the differences in particle size distribution among the slope positions remains unclear but it might be attributed to the different intensities of mineral weathering and the different extent of clay eluviation relative to the slope position; the subtle difference in soil hydrologic conditions and landform processes relative to the slope position might lead to some difference in the particle size distribution (within the same texture category) and clay mineral composition. This speculation can be partially supported by our findings of a larger extent of increase in clay at the subsoils in LS compared to those in US and MS and the higher clay activity index at LS compared to US and MS. The topographic position affects the allocation of water and transformation and translocation of materials on the lateritic soil landscapes (Zhang *et al*. 2004b). At the upper slope, the intensive weathering of minerals and leaching of bases would result in the accumulation of low-activity clays; on the contrary, at the lower slope, less effective drainage hinders leaching of the bases and mineral weathering leading to the soils possibly containing greater amounts of bases and active clays such as smectite and chlorite (Zhang *et al*. 2004a; Abe *et al*. 2009).

CONCLUSION AND RECOMMENDATIONS

The findings of this study revealed that the lateritic soils at the study site have several constraints against agricultural production, including strong acidity along with Al toxicity risk, low availability of crop nutrients, and imperfectly drained characteristics after heavy and/or continual rains. Soil acidity and deficient level of Ca are the top-priority issues as indicated by soil pH and exchangeable Ca which were lower than their optimal ranges for mango production (DOA 2009; Poffley and Owens 2005). Furthermore, we found higher variations of both vertical and horizontal directions for the soil variables related to fertilizer-derived nutrients, i.e. total N, available P, and exchangeable K and Mg, than the others and preferential accumulation of soil organic matter and nutrients such as total N and available P at LS and/or MS positions than in the US layer. Based on the findings of this study, we recommend the following key management practices for sustainable mango production in the study region: (1) use of lime, (2) incorporation of organic manure, and (3) precision application of fertilizers.

(1) Liming

Exchangeable Al concentration in the studied soil was found to range from moderate (0.5–1.0 $cmol_c$ kg^{-1}) to high levels (1.0–2.5 $cmol_c$ kg^{-1}). This condition is judged as an Al toxicity risk as the Al saturation (16.2 ± 6.2%) is higher than 11% (Nyi *et al*. 2017). The application of lime is crucial to efficiently ameliorate soil acidity and strongly acidic soil pH (Correia *et al*. 2018) to the optimum pH range (5.5–6.5) for mango cultivation (DOA 2009). This is also beneficial to replenishing Ca in the soil (Brady and Weil 2008). Our findings suggest that a larger amount of lime may be required at MS and LS than in US due to the higher Al saturation in those layers.

(2) Organic manure incorporation

As a medium to long-term soil management strategy to improve soil fertility potential, the application of organic manures is recommended to increase soil organic matter content which was currently found in low (< 14 g kg^{-1}) to medium (15–29 g kg^{-1}) levels (Nyi *et al*. 2017). This practice is also favourable to replenishing soil nutrients and enhancing CEC. Our findings suggest that a larger amount of organic manure can be applied in US than in the MS and LS along with the control of soil erosion to prevent the translocation of organic matter to the lower slopes.

(3) Precision fertilizer application

The application of NPK fertilizers can effectively increase the mango yield (Zhang *et al*. 2019), considering the low levels of total N, available P, and exchangeable K in the studied soils. However, with the substantial spatial (both horizontally and vertically) variation of fertilizer-derived nutrients in the studied soil, it is desirable to apply fertilizers in a precision approach using straight rather than compound fertilizers. In particular, the accumulation and uneven distribution of available P in the topmost soil layer need special care at the study site.

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