Research Article

Comparative Analysis of Soil Fertility in Sandy Soils along a Toposequence Transect in Sandai, West Kalimantan

Analisis Perbandingan Penilaian Kesuburan Tanah pada Tanah Berpasir sepanjang Toposekuen di Sandai, Kalimantan Barat

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Abstract: Addressing food crises and land degradation potential requires multisteps agricultural development, including soil fertility assessment. This study evaluates sandy soil fertility status along a toposequence transect in Sandai District, Ketapang Regency, West Kalimantan. Seven observation points (TP1, TP2, TP3, TK1, TK2, TK3, and TK4) were established, with soil samples collected from depths of 0-30 cm and 30-60 cm. Soil fertility assessment was conducted using three criteria: Five Major Soil Chemical Properties (FMSCP), Basic Cation Saturation Ratio (BCSR), and Sufficiency Level of Available Nutrients (SLAN). The FMSCP method exhibited low to very low fertility statuses, while the BCSR and SLAN methods revealed significant variations in soil fertility, ranging from deficient to excessive. Both the BCSR and SLAN methods demonstrated strong relationships with soil parent material and slope gradient, as evaluated through a multivariate approach. The BCSR method indicated deficient to balanced status at all profile points, whereas dominant balanced to excessive statuses were observed at all fertility points. The SLAN national criteria predominantly indicated deficient status for calcium (Ca), magnesium (Mg), and potassium (K), while the international criteria identified K deficiency only. This study served as forums to discuss fertility assessment in tropical soils. Also, recommends the potential for implementing the FMSCP criteria-based soil fertility assessment method for tropical Indonesian sandy soils and consider the involvement of balancing ratios in a more comprehensive soil fertility evaluation approach.

Keywords: BCSR, FMSCP, soil-fertility-assessment, SLAN, toposequence

Abstrak: Mengatasi krisis pangan dan potensi degradasi lahan memerlukan pengembangan pertanian bertahap, termasuk penilaian kesuburan tanah. Penelitian ini mengevaluasi status kesuburan tanah berpasir di sepanjang transek toposekuen di Kecamatan Sandai, Kabupaten Ketapang, Kalimantan Barat. Tujuh titik pengamatan (TP1, TP2, TP3, TK1, TK2, TK3, dan TK4) ditetapkan, dengan sampel tanah diambil dari kedalaman 0-30 cm dan 30-60 cm. Penilaian kesuburan tanah dilakukan menggunakan tiga kriteria: Lima Sifat Kimia Tanah Utama (FMSCP), Rasio Kejenuhan Kation Basa(BCSR), dan Tingkat Kecukupan Ketersediaan Hara (SLAN). Metode FMSCP menunjukkan status kesuburan yang rendah hingga sangat rendah, sementara metode BCSR dan SLAN menunjukkan variasi signifikan dalam kesuburan tanah, mulai dari defisiensi hingga kelebihan. Baik metode BCSR maupun SLAN menunjukkan hubungan yang kuat dengan bahan induk tanah dan gradien lereng, yang dievaluasi menggunakan pendekatan multivariat. Metode BCSR menunjukkan status defisiensi hingga seimbang di semua titik profil, sementara status seimbang hingga berlebihan dominan terlihat di semua titik kesuburan. Kriteria nasional SLAN sebagian besar menunjukkan status defisiensi untuk kalsium (Ca), magnesium (Mg), dan kalium (K), sementara kriteria internasional hanya menunjukkan defisiensi K. Penelitian ini merupakan forum untuk mendiskusikan penilaian kesuburan di tanah tropis. Penelitian ini merekomendasikan penerapan metode penilaian kesuburan tanah berbasis kriteria FMSCP untuk tanah berpasir di wilayah tropika Indonesia, serta mempertimbangkan keterlibatan rasio keseimbangan dalam pendekatan evaluasi kesuburan tanah yang lebih komprehensif.

Kata kunci: BCSR, FMSCP, kesuburan tanah, SLAN, toposekuen

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INTRODUCTION

Optimal soil fertility is essential for sustainable agricultural production. A multitude of methodologies have been developed to assess this critical soil quality by interpreting soil test results (Eckert 1987; Katharine and Devakumari 2022; Etienne Parent et al. 2021). In Indonesian context, the Five Major Soil Chemical Properties (FMSCP) method, as outlined by PPT (1983), is the most widely used approach for assessing soil fertility status. This method analyzes five parameters, including cation exchange capacity (CEC), base saturation (BS), total phosphorus (P) and potassium (K), and organic carbon (C-org). Another classical approach that has gained traction is the Basic Cation Saturation Ratio (BCSR) method, in which the concept originated from Bear and his colleagues works (Bear and Prince 1945; Bear et al. 1951). Popularized by Albrecht (1975), this method adheres to the theory of balancing the ideal ratio of the availability of three essential base cations in soil (Ca, Mg, and K) to improve soil health and nutrient availability. The third method, Sufficiency Level of Available Nutrients/SLAN or Critical Cation Deficiency Status/CCDS, determines critical concentration thresholds for specific base cations. Plants respond to fertilizer application when soil cation concentrations fall below these critical or sufficiency levels (Eckert 1987; Haby et al. 1990). While the FMSCP and SLAN/CCDS methods have been extensively utilized in Indonesia, particularly during the transmigration era of the 1980s and 1990s, the BCSR method appears to be underrepresented in the national research landscape.

Despite criticisms for its oversimplified "*balancing nutrients*" concept and lack of scientific evidence (Eckert and McLean 1981; Eckert 1987; Koppitke and Menzies 2007; McLean 1977; McLean et al. 1983), recent scholarly works have developed a more nuanced understanding of BCSR method. These studies have unveiled its widespread practices across fields, laboratories, and agriculture-based consulting (Brock et al. 2021a; Brock et al. 2021b; Chaganti and Culman 2017; Culman et al. 2021). Furthermore, extensive research and practical application of BCSR and SLAN methods have been conducted in subtropic or temperate regions, particularly in Europe and North America (Chaganti et al. 2021; Favaretto et al. 2008; Jhonston 2011; Randall et al. 1997; Soto et al. 2023; Sprunger et al. 2021; Stevens et al. 2005). In contrast, assessment on these methods in tropical region, especially on sandy-textured soils remains relatively under-explored (Anda et al. 2012; Pulunggono et al. 2022; Sabudu et al. 2021; Souza et al. 2016).

A comparative analysis of these methods under tropical sandy soils is thus imperative to inform optimal soil management practices. This study evaluates the fertility assessment of BCSR, SLAN, and FMSCP methods in tropical sandy soils along the toposequence transect, which exhibited variety of soil types in close proximity. Also, using multivariate approach, this study extended the question on how far the soil forming factors (parent materials and topography) could affects sandy soil characteristics, especially on particular subsets based on fertility criteria. The findings of this research are expected to provide valuable insights for enhancing agricultural productivity and sustainability in regions with similar soil conditions.

MATERIALS AND METHODS

Site Description and Sampling Campaign

The study was conducted in Sandai District, West Kalimantan Province, Indonesia. The study site is generally a lowland eastern part of the Schwaner Mountains, which primarily influences its diverse topographical and pedological landscapes (Figure 1, Table 1; Breitfeld et al. 2020; Rustandi and de Keyser 1993). The site region exhibited a range of altitudes (0-255 m), encompassing over six soil types and five parent materials, *i.e.,* sandstone and claystone from Ketapang complex, basaltic rocks from Kerabai volcanics, and granites from Sukadana granites fromations (Breitfeld et al. 2020; Rustandi and de Keyser 1993). The study site received high precipitation, about 3756 mm annually (BPS Kecamatan Sandai 2023).

To capture soil variability, an approximately 16 km toposequence transect (Figures 1a and 1b) traversed a dryland secondary forest, perpendicular to contour lines and Lekah river within Randau and Mekarsari Villages. This transect constituted three profile samples (TP1, TP2, and TP3) and four fertility samples (TK1, TK2, TK3, and TK4) spatially representing two major land systems, namely Honja and Palakunai (RePPProT 1987). All soil samples were collected using soil auger (approximately 250 g) at 0-30 cm and 30-60 cm depths. Profile samples were subsequently converted to equivalent fertility depths through weighted averaging.

Laboratory Analyses

The laboratory determination of soil physicochemical properties was carried out at the Department of Soil Science and Land Resource Management, Faculty of Agriculture, IPB University. All studied samples were firstly air-dried, ground, and passed through a 2-mm sieve. Soil texture was determined by the pipette method. Actual and potential acidities were potentiometrically measured using 1:1 soil-to-solution ratio of H_2O and KCl, respectively. Cation exchange capacity (CEC) and exchangeable base cations (Ca, Mg, K) were extracted by NH_4OAc N pH 7. The extracts were then quantified using atomic absorption spectrophotometer/AAS Shimadzu AA-6300 for Ca and Mg and flame photometer PFP7 Jenway for K. Total P and K were extracted by titration using HCl 25%, whereas available P was extracted using Bray-1 method. Organic carbon (C-org) and total nitrogen (N) contents were determined by digesting soil samples under dichromate (Walkley and Black 1934) and sodium hydroxide (Kjeldahl method), respectively, then, the concentrations were calculated through titration. Lastly, the exchangeable acids (Al and H) were determined using KCl titration. Base saturation/BS was determined as the proportion of the sum of exchangeable base cations (K^+, Na^+, Ca^{2+}, and Mg^{2+}) to the total CEC, expressed as a percentage. Ca, Mg, and K saturations were calculated as percentage to total exchangeable cations (acid+base cations). We also apply similar calculation for total acid saturation/AS using summation of all acid cations.

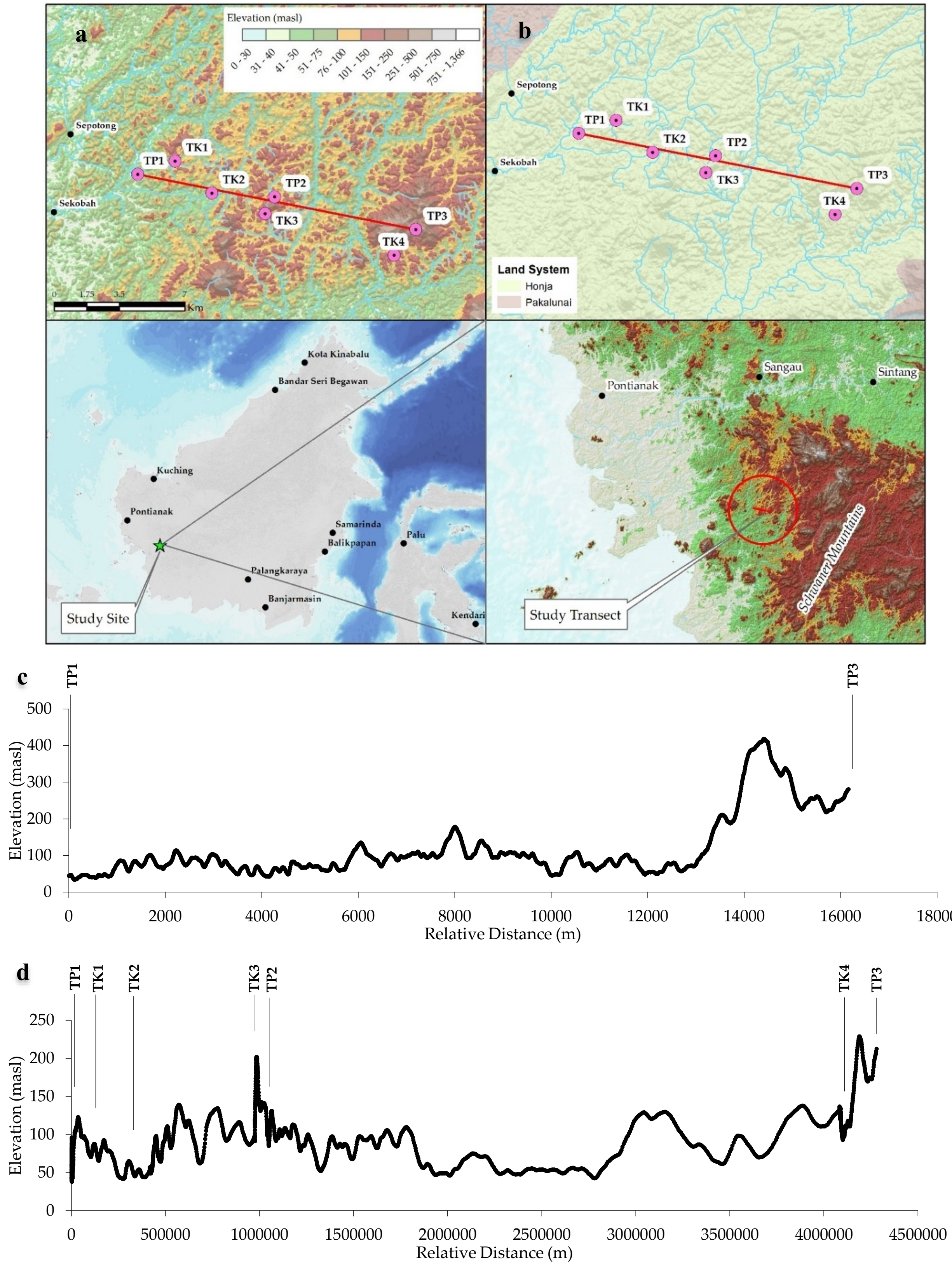

Figure 1. Map of the Research Location depicting (a) topography, (b) land system, and elevation profiles of (c) TP1-TP3 transect and (d) crossed all observation points

For general characterisation, the enrichment percentage of soil properties in the upper depth (0–30 cm) was calculated using the following equation:

$$EP\ (\%) = \frac{UC - LC}{LC} \times 100\%$$

which EP represent the enrichment percentage of soil properties at upper depth (0 – 30 cm), whereas UC and LC represent the value/concentration of soil parameters sampled at upper (0 – 30 cm) and lower (30 – 60 cm) sampling depth.

Soil Fertility Assessment Criteria

Soil fertility status was assessed using three methods, *i.e.,* Five Major Soil Chemical Properties/FMSCP, Basic Cation Saturation Ratio/BCSR, and Sufficiency Level of Available Nutrients/SLAN or Critical Cation Deficiency Status/CCDS. The FMSCP analysis was conducted using the TOR P3MT Type B criteria established by PPT (1983) during transmigration era. It is primarily assessed soil chemical properties *i.e.,* CEC, BS, total P and K, and C-org. BCSR and SLAN methods were determined based on exchangeable K, Ca, and Mg using both Indonesian and international criteria. For Indonesian BCSR and SLAN, we applied the median level of criteria reported by Eviati et al. (2023). Furthermore, Baker and Amacher (1981) criterion was chosen as international standard to interpret BCSR. We also applied Albrecht ideal saturation ranges of60–75% for Ca, 10–20% for Mg, 2–5% for K (Albrecht 1975). Moreover, Australian criteria (Aitken and Scott 1999; Bruce 1999; Gourley 1999) was selected to be used as SLAN' critical level. Soils were classified as D (Deficient) or E (Excessive) for BCSR and SLAN values outside the specified ranges, and B (Balanced) or S (Sufficient) for values within these ranges, respectively. The entire assessment method employed in this study is presented at Tables 2, 3, and 4.

Table 1. Criteria for Assessing Soil Fertility Status based on FMSCP

CEC	BS	Total P and K, and C-Org	Fertility Status
H	H	≥ 2 H, without L	High
		≥ 2 H, with L	Medium
		≥ 2 M, without L	High
		≥ 2 M, with L	Medium
		HLM	Medium
		≤ 2 L, with H	Medium
		≤ 2 L, with M	Low
H	M	≥ 2 H, without L	High
		≥ 2 H, with L	Medium
		≥ 2 M	Medium
		other combinations	Low
H	L	≥ 2 H, with L	Medium
		≥ 2 H, without L	Low
		other combinations	Low
M	H/M	≥ 2 H, without L	Medium

CEC	BS	Total P and K, and C-Org	Fertility Status
		≥ 2 M, without L	Medium
		other combinations	Low
M	L	3 H	Medium
		other combinations	Low
L	H	≥ 2 H, without L	Medium
		≥ 2 H, with L	Low
		≥ 2 M, without L	Medium
		other combinations	Low
L	M	≥ 2 H, without L	Medium
		other combinations	Low
L	L	all combinations	Low
VL	H/L/M	all combinations	Very Low

Notes: H (high); M (moderate); L (low); VL (very low); CEC (cation exchange capacity); BS (base saturation). This category is based on Eviati et al (2023). Example using first row: Fertility status = H if, CEC = H, BS = H, and the combination of H+H+H, H+H+VL, H+VL+VL, or VL+VL+VL (can be reversed/shifted) in Total P and K and CEC.

Table 2. Criteria for Assessing Soil Fertility Status based on BCSR

BCSR Criteria	Ca:Mg	Ca:K	Mg:K
International	3:1 - 8:1	12:1 - 40:1	2:1 - 10:1
Indonesian (Pusat Penelitian tanah)	4.9:1	19.5:1	4:1

Table 3. Criteria for Assessing Soil Fertility Status based on SLAN

SLAN Criteria	Ca	Mg	K
	------------------------------------ me/100g	------------------------------------	
International	0.5 - 1.5	0.2 - 0.3	0.2 - 0.5
Indonesian (Pusat Penelitian Tanah)	6.0 - 10.0	1.1 - 2.0	0.4 - 0.5

Statistical Analyses

The data in this study was compiled using Microsoft Excel. The statistical analysis was performed in R environment using RStudio 4.3.2. Map was processed and laid out using ArcGIS 10.8. A principal component analysis (PCA) was performed using `FactoMineR` (Husson et al. 2024) and `factoextra` (Kassambara and Mundt 2022) to obtain multivariate differences between classes constructed by multiple input subsets of the data, *i.e.,* all/original, FMSCP, BCSR, and SLAN-based datasets.

RESULTS AND DISCUSSION

Soil Properties Along the Toposequence Transect with Special Relation to Geological Settings in Tropical Climate Region

Soils developed under tropical climates often undergo intense precipitation and mineral weathering, leading to erosion, cation leaching, and high acidity (Fujii 2014; Hartemink 2002). These climatic factor, parent material, and topography reshape the soil formation, which in our study site occurs at an adjacent location. Three profiles excavated along the transect revealed a variety of distinct soils as shown in Tables 4 and 5. Besides their similarity in high sand content and low to very low CEC, TP1 soil possessed psammentic and dystric properties, representing high sand content and poor fertility at its upper surface. More reddish color throughout soil solum reflecting high sesquioxide content was shown by an oxic TP2 soils. Meanwhile, TP3 showed a short solum with argillic horizon and lithic contact, indicating matured, (might be highly) eroded soils with concurrent podzolization process overlying sedimentary regolith. These properties represent interesting pedological examples of how diverse soils could be developed under close proximity. The soil characteristics reflect the combination of aged, siliceous, and sedimentary parent materials (sandstone and claystone) from the Ketapang complex, deposited over Jurassic to Cretaceous ages (Li et al. 2022; Breitfeld et al. 2020), that affected by newer, quaternary basaltic rocks from Kerabai volcanics and granitoids from Sukadana granites at its surrounding areas (Breitfeld et al. 2020; Rustandi and de Keyser 1993).

High acidity in tropical, weathered soils are reflected in our results in Tables 4 and 5, as TP1, TP2, and TP3 soils exhibited low status on actual and potential pH, as well as CEC and base saturation. Oppositely, these soils possessed elevated levels of Al and H, which were considerably higher than all their combined bases. Their sand contents are also relatively higher than other soils, mediating higher cation leaching, especially at high precipitation areas covering the study site. The weathering of both sedimentary rocks releases low amounts of base cations, concurrently with the accumulation of H and Al in soils throughout an extended period. In similar soils developed from sandstone in other parts of Borneo, Fujii et al (2011) reported that biogenetic acidification can be rather devastated since the sandy soils did not possess ample neutralizing capacity to counter acid cations compared to serpentinite and mudstone-derived oxic soils.

In contrast, other soils (TP3, TK1-TK4) displayed higher pH. Conversely to TP1 and TP2, BS values in TK1-TK4 soils were comparable to or exceeded exchangeable acidity levels with exchangeable Ca having the highest magnitude (Tables 4 and 5). TK1 had similar sand content in both sampling depths, whereas TK2 possessed the same trend but in lower magnitudes. Significant sand content was found at a lower depth in TK3, which increased by around 76% compared to its upper depth. TK3 was the opposite but not as high as TK1, numbering around a 48% increase (Table 5). These conditions likely occurred due to a greater proportion of weathered granite and basalts from Sukadana granite and Kerabai volcanic, respectively (Rustandi and de Keyser 1993) compared to sedimentary claystone. The second assumption is the current weathering of granitic rocks resulted in coarser-textured soils owing to its high quartz content as reported in other regions (Ma et al. 2023; Katsuyama et al. 2005; Zhang et al. 2023). Literature review and field samplings reported that the primary minerals that widely found in the study site's region (as part of Sukadana granite and Kerabai volcanic from Schwaner mountains) are biotite and hornblende, besides the dominance of quartz, alkali feldspar, plagioclase, biotite, amphibole, titanite, apatite, hornblende and epidote at several closest rock samples (Breitfeld et al. 2020; Hennig et al. 2017; Sutarto et al. 2022; van Hattum et al. 2013; Qian et al. 2022) provide evidence for the second assumption. High quartz content contributes to sandy-textured soils. The weathering of alkali feldspar and biotite minerals releases high K. Furthermore, Ca came from plagioclase degradation, whereas hornblende and amphibole weathering gave rise to Mg. However, high degrees of weathering and leaching in tropical climate might provoked mobile cations like K to be leached out from the soil systems (Marschner and Rengel 2023), as shown by very low exchangeable K in all studied soils in Tables 4 and 5.

Generally, the soil chemical properties were greater towards the surface (Tables 4 and 5), as indicated by positive EP among observed parameters (Figure 2). The enrichment patterns were more pronounced for litter-derived parameters like C-org and total N, and mobile nutrients, such total and exchangeable K and Na, respectively. Other parameters except for P showed minimal differences (< 15%) between upper and lower sampling depths, indicating negligible surface enrichments. However, the studied soils exhibited a negative but negligible total P enrichment (Figure 2). This condition can be attributed to low P influx derived from the soil's parent materials, such as apatite (van Hattum et al. 2013).

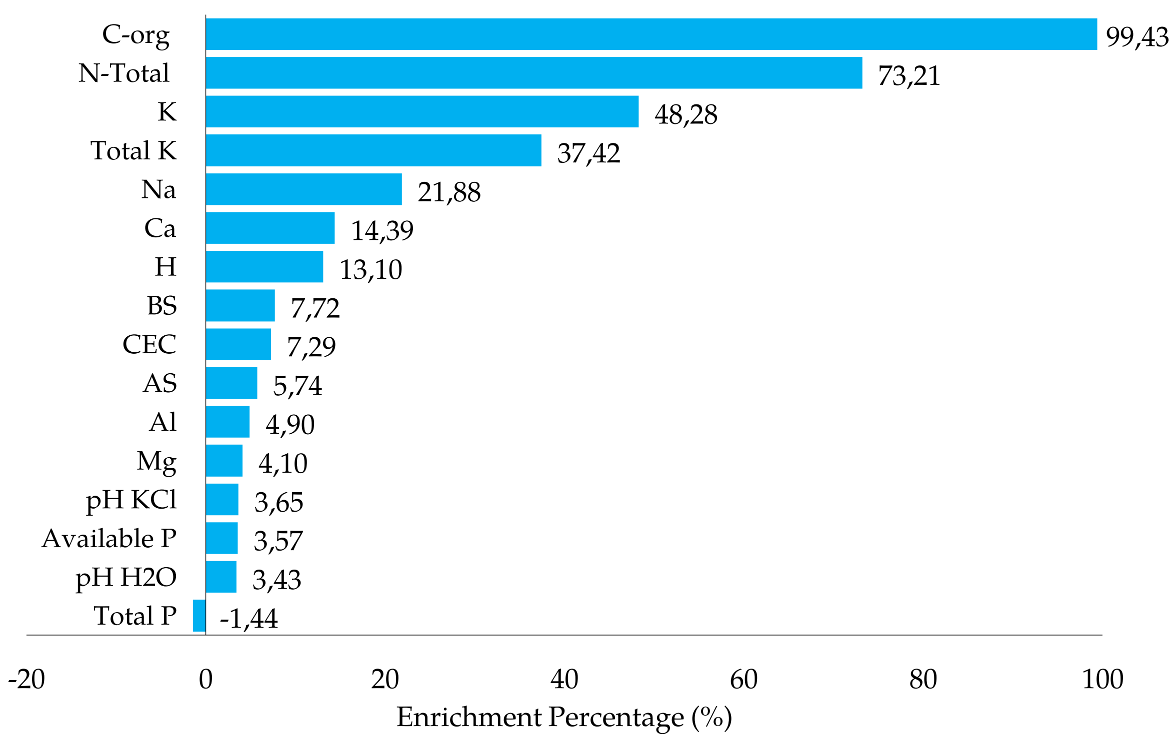

Figure 2. The Enrichment Percentage/EP of several Nutrient in Studied Soils

Table 4. Physicochemical properties of soil profiles collected along the toposequence transect

Profile	Depth	------ pH ------		Org-C	Total N	Available P	----- Exchangeable Bases -----				CEC	BS	Exchangeable Acids		Fine Earth Fractions			Texture Classes	Total Cations	Al Saturation
							Ca	Mg	K	Na			Al	H	Sand	Silt	Clay			
	-- cm --	H_2O	KCl	---------- % ----------		mg/kg P_2O_5	------------------ me/100g ------------------					- % -	------- me/100g -------		----------- % -----------				-- me/100g --	---- % ---
Psammentic Dystrudept, *Rolling (8-15%), Sandstone and claystone*																				
TP1	0 - 25	4.00	3.40	2.39	0.18	9.62	1.21	0.30	0.12	0.27	5.48	34.67	9.12	0.64	67.84	12.61	19.55	Sandy loam	11.66	78.22
	25 - 43	4.40	3.80	0.95	0.12	8.02	1.19	0.29	0.10	0.19	4.93	35.90	7.38	0.52	58.58	15.95	25.47	Sandy clay loam	9.67	76.32
	43 - 75	4.60	4.00	0.55	0.07	9.62	1.06	0.27	0.07	0.15	4.70	32.98	5.96	0.37	55.99	20.13	23.88	Sandy clay loam	7.88	75.63
	75 - 130	4.80	4.20	0.16	0.02	9.85	1.07	0.29	0.10	0.19	4.48	34.09	1.82		54.93	21.00	24.07	Sandy clay loam	3.81	47.77
Oxic Dystrudept, *Rolling (8-15%), Sandstone, claystone, basalt*																				
TP2	0- 12	4.00	3.40	2.55	0.19	15.35	1.11	0.37	0.12	0.12	6.34	27.13	9.76	0.62	47.24	14.29	38.47	Sandy clay loam	12.10	80.66
	12 - 35	4.10	3.50	0.95	0.08	11.91	0.97	0.35	0.18	0.21	5.72	29.90	8.22	0.54	55.43	17.49	27.08	Sandy clay loam	10.47	78.51
	35 - 50	4.70	4.00	0.38	0.04	9.62	0.95	0.33	0.06	0.12	5.60	26.09	5.38	0.42	54.03	9.43	36.54	Sandy clay	7.26	74.09
	50 - 70	4.60	4.00	0.32	0.04	9.62	0.92	0.30	0.11	0.19	5.39	28.20	6.44	0.47	59.95	9.90	30.15	Sandy clay loam	8.43	76.39
Lithic Kandiudult, *Hillocky (25-40%), Basalt, sandstone*																				
TP3	0 - 18	4.90	4.20	0.87	0.09	10.76	1.31	0.40	0.18	0.29	5.86	37.20	4.82	0.35	47.83	20.38	31.79	Sandy clay loam	7.35	65.58
	18 - 40	4.60	3.90	0.80	0.06	10.76	1.05	0.36	0.13	0.31	5.24	35.31	7.10	0.42	48.66	25.72	25.62	Sandy clay loam	9.37	75.77

Table 5. Soil physicochemical properties along the transect, aggregated to two depths (0-30 and 30-60 cm)

Observation Points	Sampling Depth	--- pH ---		C-org	N-Total	CN	-------- P --------		--- K ---	Exchangeable Bases				CEC	BS	Exchangeable Acids		Texture		
		H_2O	KCl				Available	Total	Total	Ca	Mg	K	Na			Al	H	Sand	Silt	Clay
	cm			-------- % --------			---- mg/kg P_2O_5 ----		mg/kg K_2O	---------- me/100g ----------					%	------ me/100g -----		------------ % ------------		
Psammentic Dystrudept, *Rolling (8-15%), Sandstone and claystone*																				
TP1	0 - 30	4.1	3.5	2.15	0.17	12.65	9.3	n.d	n.d	1.21	0.30	0.12	0.26	5.39	34.86	8.82	0.62	66.27	13.18	20.56
	30 - 60	4.5	3.9	0.72	0.09	8.00	8.9	n.d	n.d	1.12	0.28	0.08	0.17	4.80	34.27	6.57	0.43	57.1	18.33	24.56
Oxic Dystrudept, *Rolling (8-15%), Sandstone, claystone, basalt*																				
TP2	0 - 30	4.1	3.5	1.59	0.12	13.25	13.3	n.d	n.d	1.03	0.36	0.16	0.17	5.97	28.72	8.84	0.57	52.15	16.21	31.64
	30 - 60	4.6	4.0	0.46	0.05	9.20	10.0	n.d	n.d	0.94	0.32	0.10	0.16	5.55	27.43	6.21	0.46	56.22	10.96	32.82
Lithic Kandiudult, *Hillocky (25-40%), Basalt, sandstone*																				
TP3	0 - 30	4.9	4.2	0.87	0.09	9.67	10.8	n.d	n.d	1.31	0.40	0.18	0.29	5.86	37.20	4.82	0.35	47.83	20.38	31.79
	30 - 60	4.6	3.9	0.80	0.06	13.33	10.8	n.d	n.d	1.05	0.36	0.13	0.31	5.24	35.31	7.10	0.42	48.66	25.72	25.62
Typic Kanhapludult, *Hillocky (25-40%), Basalt, sandstone*																				
TK1	0 - 30	5.3	4.5	1.43	0.15	9.53	7.8	79.9	165.7	3.71	0.51	0.14	0.17	9.14	49.56	0.93	0.26	47.62	17.31	35.07
	30 - 60	5.1	4.4	0.42	0.05	8.40	9.4	88.4	147.6	3.10	0.50	0.10	0.17	6.29	61.53	1.46	0.21	50.17	13.36	36.47
Typic Kandiudult, *Small hillocky (15-25%), Sandstone, claystone, granite*																				
TK2	0 - 30	4.8	4.1	1.51	0.15	10.07	8.2	82.2	142.8	2.63	0.39	0.10	0.30	5.19	65.90	0.62	0.24	31.36	46.86	21.78
	30 - 60	4.7	4.0	0.52	0.06	8.67	7.1	73.5	73.5	2.08	0.46	0.04	0.16	6.86	39.94	0.89	0.20	20.08	51.40	28.52
Typic Kanhapludult, *Hillocky (25-40%), Basalt, sandstone*																				
TK3	0 - 30	5.0	4.3	1.51	0.15	10.07	13.5	134.9	107.9	1.92	0.34	0.08	0.15	4.94	50.40	1.90	0.28	17.32	58.75	23.93
	30 - 60	4.5	3.8	0.95	0.10	9.50	14.4	146.8	97.0	1.86	0.31	0.08	0.15	4.82	49.79	1.78	0.25	73.04	11.17	15.79
Typic Kandiudult, *Small hillocky (15-25%), Sandstone, claystone, granite*																				
TK4	0 - 30	5.0	4.3	1.35	0.14	9.64	9.6	99.6	110.3	2.82	0.49	0.08	0.22	6.64	54.37	1.68	0.27	55.85	13.57	30.58
	30 - 60	4.1	3.4	1.35	0.15	9.00	9.4	93.7	65.1	2.64	0.45	0.05	0.16	6.48	50.93	2.31	0.32	29.08	27.27	43.65

Notes: n.d. not determined.

Citation:
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Soil Fertility Assessment using FMSCP, BCSR, and SLAN

As presented in Tables 6, CEC in all studied soils was classified as low (L), except for TK3 which possessed very low (VL) CEC. P, K, and C-org were classified as L to VL. In contrast, BS exhibited more diverse classes, ranging from L in TP1 and TP2 to high (H) and moderate (M) in TK1, TK2, and TK4. Consequently, all soils in all sampling depth were categorized as having low fertility, except for TK3 which possessed very low soil fertility. None of the studied soils were classified as medium or high fertility. Very low fertility on both TK3's sampling depths were predominantly contributed by very low CECs. It can be understood that more weight is stressed on CEC, since tropical region undergo high precipitation and rapid mineral weathering. This condition would result in higher risk of nutrient leaching (Fujii 2014; Hartemink 2002). Higher CEC soils maintain cations in check, bonds with their exchange complexes and prevents leaching. Contrastingly, soils possessing lower CECs, even though initially had abundant cations, they posing significant leaching due to higher concentration of free, unexchanged cations (Juo and Franzluebbers 2003; Marschner and Rengel 2023).

The FMSCP soil fertility status in Table 6, which spanned a range from very low (VL) to low (L), was significantly influenced by the presence of low soil CEC. The explanation of low CEC linked to the soil texture (or fine earth fractions) and organic matter content. The dominant texture in the studied soils classified as sandy class, which sand content generally accounts around 40 to 60 % (Tables 4 and 5). With addition of organic C contents exceeding averages in tropical soils (1.3 to 2 %; Tables 4 and 5), this condition might result in low to moderate CEC values if the clay fraction possess high activity. However, contrasting results were observed in our study site, which apparently due to the small surface area of low activity clays or simply from the functional groups from organic materials. Prasetyo and Suharta (2004) reported similar condition in sandy soils located at South Kalimantan, where the soils clays consisted predominantly of goethite, hematite, dan gibbsite.

Table 6. Assessment of soil fertility status based on the FMSCP method

Observation Point	Depth	CEC	BS	Total P	Total K	C-org	Fertility Status
	cm						
TP1	0-30	L	L	n.d.	n.d.	M	L
	30-60	L	L	n.d.	n.d.	VL	L
TP2	0-30	L	L	n.d.	n.d.	L	L
	30-60	L	L	n.d.	n.d.	VL	L
TP3	0-30	L	M	n.d.	n.d.	VL	L
	30-60	L	L	n.d.	n.d.	VL	L
TK1	0-30	L	M	VL	L	L	L
	30-60	L	H	VL	L	VL	L
TK2	0-30	L	H	VL	L	L	L
	30-60	L	M	VL	VL	VL	L
TK3	0-30	VL	M	L	L	L	VL
	30-60	VL	M	L	VL	VL	VL
TK4	0-30	L	H	VL	L	L	L
	30-60	L	M	VL	VL	L	L

Citation:
Pulunggono HB, Pratiwi D, Zulfajrin M, Nurazizah LL, Chahyahusna A, Iskandar. 2024. Comparative Analysis of Soil Fertility in Sandy Soils along a Toposequence Transect in Sandai, West Kalimantan. *Celebes Agricultural*. 5(1): 1-24. doi: 10.52045/jca.v5i1.779

Similar to FMSCP, the BCSR assessment in Table 7 and Figure 3 revealed a striking spectrum of deficiencies to excesses across profiles, leaving none of them acquired fully balanced statuses. Meanwhile, fertility observation points exhibited a range of balanced to excessive fertility statuses. Overall, cation ratios at TP1, TP2, and TP3 ranged from deficient to balanced, while TK1, TK2, TK3, and TK4 predominantly exhibited balanced to excessive ratios. The presence of deficient and excessive cation ratios at several locations indicates cation imbalance. Balanced cation ratios, essential for optimal plant growth and development (Pulunggono et al. 2022), are achieved within the following ranges: Ca:Mg = 3.0:1–8.0:1, Ca:K = 12.0:1–40.0:1, and Mg:K = 2.0:1–10.0:1 (Baker and Amacher 1981). According to PPT (1983), the ideal ratios are Ca:Mg = 4.9:1, Ca:K = 19.5:1, and Mg:K = 4:1, derived by adjusting midpoint values to align with national SLAN criteria (Table 7). Using Albrecht ideal saturation ranges simulated using histogram frequencies (Figure 3; Albrecht 1975), most studied soils fall below ideal Ca and Mg saturations, while the opposite pattern was shown by K saturation.

Table 7. Assessment of soil fertility status based on the BCSR method

Observation Point	Depth	Ca:Mg	Ca:K	Mg:K	Baker dan Amacher (1981)			Pusat Penelitian Tanah (1983)		
	cm				Ca:Mg	Ca:K	Mg:K	Ca:Mg	Ca:K	Mg:K
TP 1	0-30	4.03:1	10.21:1	2.52:1	B	D	B	D	D	D
	30-60	4.00:1	13.71:1	3.42:1	B	B	B	D	D	D
TP 2	0-30	2.86:1	6.50:1	2.27:1	D	D	B	D	D	D
	30-60	2.92:1	9.57:1	3.27:1	D	D	B	D	D	D
TP 3	0-30	3.27:1	7.27:1	2.22:1	B	D	B	D	D	D
	30-60	2.91:1	8.07:1	2.76:1	D	D	B	D	D	D
TK 1	0-30	7.27:1	26.50:1	3.64:1	B	B	B	E	E	D
	30-60	6.20:1	31.00:1	5.00:1	B	B	B	E	E	E
TK 2	0-30	6.74:1	26.30:1	3.90:1	B	B	B	E	E	D
	30-60	4.52:1	52.00:1	11.50:1	B	E	E	D	E	E
TK 3	0-30	5.64:1	24.00:1	4.25:1	B	B	B	E	E	E
	30-60	6.00:1	23.25:1	3.87:1	B	B	B	E	E	D
TK 4	0-30	5.75:1	35.25:1	6.12:1	B	B	B	E	E	E
	30-60	5.86:1	52.80:1	9.00:1	B	E	B	E	E	E

Notes: D (*Deficient*); B (*Balanced*); E(*Excessive*)

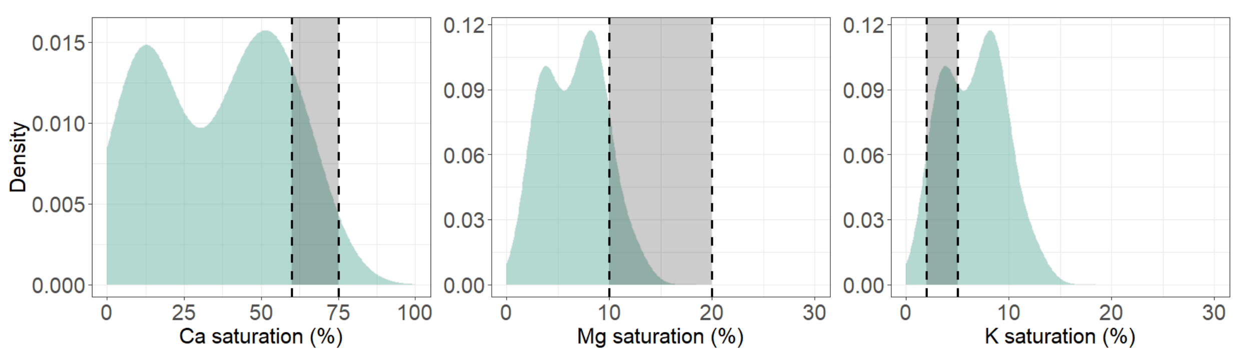

Figure 3. Histogram distribution of Ca, Mg, and K saturations at the studied soils with shaded areas representing Albrecht ideal saturation ranges across base cations (60–75% for Ca, 10–20% for Mg, 2–5% for K)

As expected, interpretation using SLAN method (Table 8) exhibited a dichotomy between national and international criteria. The national SLAN method (PPT 1983) indicated widespread deficiencies in Ca, Mg, and K. Meanwhile, the studied soils underwent K deficiency according to international SLAN standards, in contrast to sufficient to excessive levels of other cations. Furthermore, Mg emerged as a dominant element with excessive status, except at TP1, where it was classified as sufficient. This difference can be attributed to a high weathering capacity in the tropical region, especially at the study site. Furthermore, a relatively high soil Mg in several observation points using the international SLAN standard might be derived from basalt rocks containing high ferromagnesian minerals (Breitfeld et al. 2020; Rustandi and de Keyser 1993).

Table 8. Assessment of soil fertility status based on the SLAN method

Observation Point	Depth	----------- National -----------			----------- International -----------		
	cm	Ca	Mg	K	Ca	Mg	K
TP 1	0-30	D	D	D	S	S	D
	30-60	D	D	D	S	S	D
TP 2	0-30	D	D	D	S	E	D
	30-60	D	D	D	S	E	D
TP 3	0-30	D	D	D	S	E	D
	30-60	D	D	D	S	E	D
TK 1	0-30	D	D	D	E	E	D
	30-60	D	D	D	E	E	D
TK 2	0-30	D	D	D	E	E	D
	30-60	D	D	D	E	E	D
TK 3	0-30	D	D	D	E	E	D
	30-60	D	D	D	E	E	D
TK 4	0-30	D	D	D	E	E	D
	30-60	D	D	D	E	E	D

Notes : D (*Deficient*); S (*Sufficient*); E(*Excessive*)

Multivariate Approach on Soil Fertility's Comparative Assessments

The analysis utilized the highest possessed variability of principal components such as PC1 and PC2 in Figures 4 and 5. The influential variables in Figures 4a and 4b revealed that PC1 consists of chemical properties originating from soil parent materials such as base cations, cation ratios, and soil pH. Furthermore, vegetation-derived soil characteristics, *i.e.,* total N and organic C primarily contributed to PC2. Moreover, soil variables representing the combined influences of soil parent materials and vegetation were loaded into PC3 (data not presented).

This study also found that reducing the dataset to more focused variables based on certain fertility assessments can heighten variability representativeness in each PC. As can be observed, the total represented variability increased dramatically from 45.3% in using all datasets to 72.8, 83.5, and 99.8% in using FMSCP, BCSR, and SLAN-based input datasets. A 95% multivariate interval confidence showed that parent material, slope gradient, and depth significantly influenced soil properties. The influence of these three factors was more prominent in FMSCP and BCSR compared to SLAN and all datasets, as seen in the occurrences of little- or slightly overlapping circles compared to mostly- and fully overlapping circles in Figure 5.

According to Figures 4 and 5, parent material and slope gradient are the primary factors influencing parameters in the three soil fertility assessment methods. Soil derived from sandstone, siltstone, and granite parent material shows significant differences in fertility parameters compared to soil derived from sandstone and siltstone parent material. However, soil from sandstone, siltstone, and granite parent material has similar fertility characteristics to soil from basalt parent material. This supports previous findings that similarity in soil fertility parameters can be caused by long-term nutrient leaching and erosion. Topography and lithology (BIG 2024; RePPProT 1987) data suggest that erosion might occur from basalt-derived soils in high-elevation of hilly areas (Breitfeld et al. 2020; Rustandi and de Keyser 1993) down to lower, flat areas with parent materials containing sandstone, siltstone, and granite (Li et al. 2022; Breitfeld et al. 2020). In addition to the parent material, the slope gradient also influences soil chemistry and fertility, as used in FMSCP, BCSR, and SLAN assessment methods (Figure 5). The clustering pattern based on slope gradient is similar to the pattern based on parent material. All soil fertility assessment methods show similar characteristics on slopes with gradients above 15% (overlapping circles). Meanwhile, overlapping or slightly overlapping circles in Figure 5 indicate similarity in soil characteristics based on depth (0-30 cm and 30-60 cm).

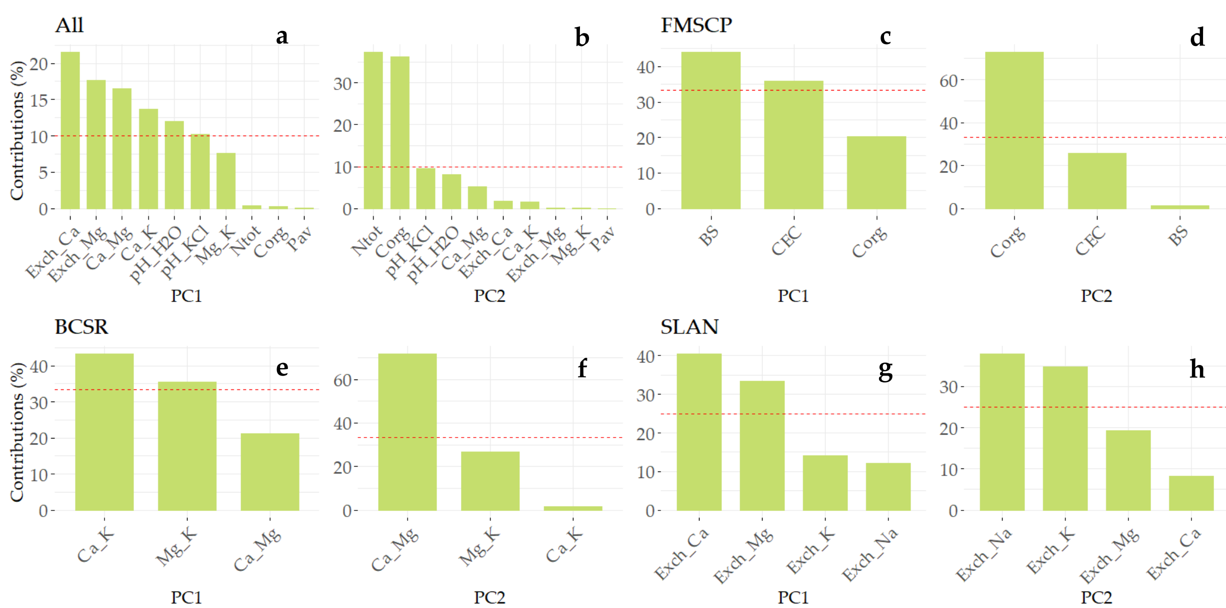

Figure 4. Variable contributions to PC1 and PC2 using (a-b) all input, (c-d) FMSCP, (e-f) BCSR, and (g-h) SLAN datasets

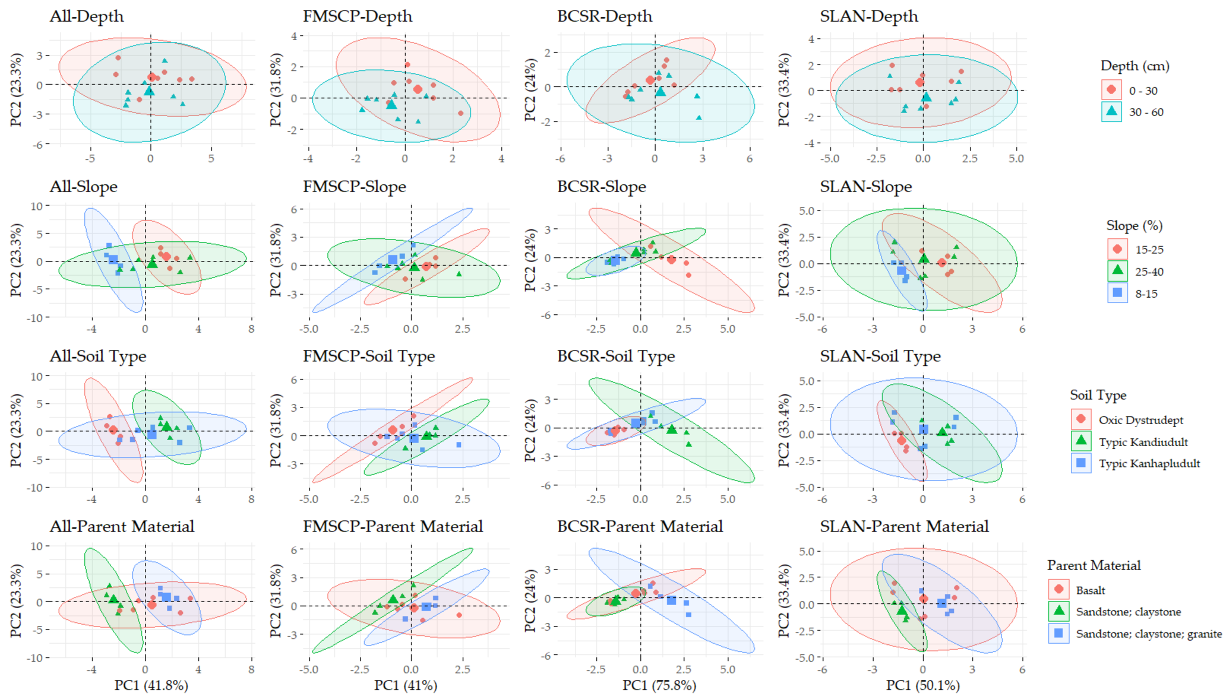

Figure 5. Clustering based on the combination of input datasets (all, FMSCP, BCSR, SLAN) and environmental factors (sampling depth, slope, soil type and parent material)

Leveraging Soil Properties and Soil Fertility Assessments to Manage Sandy Soils in Humid Tropics

The studied soils underwent cation imbalances as could be observed in Table 7 and Figure 3. This condition might have arisen from variations in parent rock composition, soil development stage (or ages), and topographical factors such as slope and position in the landscapes (Anda 2012). Due to the differences in valences and atomic radii, soil cations exhibit antagonistic interactions during plant nutrient uptake, where the dominance of certain ions can inhibit the absorption of others. This condition might occurs due to disproportionate exchangeable cation concentrations and imbalanced ratios in the soil (Hao and Papadopoulos 2003; Senbayram et al. 2015; Welte and Weyner 1963). The BCSR assessment acknowledged the significant role of exchangeable cations, as it governs cation concentration and interaction in the soil solution as well as maintains soil structure integrity (Chaganti and Culman 2017; Culman et al. 2021; Koppitke and Menzies 2007). It is essential to maintain appropriate cation ratios in improving soil flocculation, promoting efficient nutrient uptakes, and maintaining soil fertility in humid tropic areas while minimizing soil dispersion, cation leaching, and imbalanced cation uptakes.

While soil flocculation-dispersion might be a misrepresentative approach in sandy-textured and low CEC soils similar to the studied transect (Culman et al 2021; McKibben 2018; Soto 2018), an imbalanced condition of soil cations is apparently ignored in the critical thresholds approach of FMSCP and SLAN assessments. Adjusting management practices to achieve optimal Ca, Mg, and K saturations or cation ratios can alter the balance of these cations, impacting nutrient dynamics and availabilities in soil and plant root systems, thereby improving plant growth and development in both short- and long-term (Cheng et al. 2024; Garcia et al. 2022; Martin and page 1965; Takamoto et al. 2021; Wacal et al. 2019a). Cation ratios have also been developed as building blocks to other indices representing soil physicochemical properties and agriculture practices, *e.g.*, soil structural stability (Rengasamy and Marchuck 2011), net dispersive charges (Rengasamy et al. 2016), liming evaluation (Curtin and Smillie 1995), fertigation water (Souto et al. 2024) and plant tissues ratios for fertilizer evaluation (Chen et al. 2022). With respect to improving soil structures and avoiding cation antagonism, it is important to support BCSR core ideas, similar to other current research reports (Antonangelo et al. 2024; Kasno 2021; Yang et al. 2024; van Biljon et al. 2007; Wacal et al. 2019b).

Low to very low soil organic C in our study site, which also proxies for a lower level of soil total N as both parameters originated from soil organic matter/SOM. This condition could be attributed to the combination of parent material, topographic, and climate factors with the alteration of vegetation factors that contributed to a long-term decline of soil organic matter. As previously noted, soil study transect developed from a variety of sedimentary and volcanic-origin rocks containing high quartz content (Breitfeld et al. 2020; Hennig et al. 2017; Li et al. 2022; Rustandi and de Keyser 1993; Sutarto et al. 2022; van Hattum et al. 2013; Qian et al. 2022) that resulted in sandy textured soils with high erodibility (Tables 4 and 5; Fullen et al. 1998; Wischmeier and Mannering 1969). Steep slopes located at rolling to hilly areas (Figure 1) with high precipitation at humid tropic climate, facilitating rapid soil and litter erosions and SOM loss via dissolved organic matter/DOM leaching (Cotrufo and Lavallee 2022; Gharamani et al. 2011). The sampling campaign was conducted in a secondary dryland forest, which indicated that the study site had previously been logged. The higher temperature at the soil surface due to diminished shades and lower litterfall may accelerate litter decomposition and deposition during the forest succession process (Alvafritz and Hertel 2024; Guariguata and Ostertag 2001; Wang et al. 2021). All of these conditions, in turn, greatly decrease soil organic C with low recovery rate (Hattori et al. 2019; Paz et al. 2018; Villa et al. 2018), which was captured by this study as low to very low statuses (Table 6).

The BCSR and SLAN methods yielded varied results in soil fertility assessment due to cation imbalances from differing parent rock types and quantities. The imbalanced and deficient nutrient statuses that predominantly observed at BCSR and SLAN assessment highlighted a lack of cations reaching the ideal ratios and critical level, respectively, suggesting further improvement to increase the cation concentration using organic or inorganic fertilizers. As outlined by Anda (2012), Eckert and McLean (1981), Eckert (1987), McLean (1977), and McLean et al. (1983), SLAN approach was more effective in interpreting soil base cations compared to the BCSR method, which had limited applicability in assessing soil fertility at sandy-textured and low CEC soils (Culman et al 2021; McKibben 2018; Soto 2018) especially at the studied site.

Soils with high sand content are susceptible to nutrient leaching due to their low CEC, in our case, resulting from low-activity clays and minimal organic matter contribution (Tables 4 and 5). Low CEC limits the soil's ability to retain cations, which causes an initial surplus of free or unexchanged cations in soil solution. Although this surplus may provide short-term benefits for plant growth, the long-term depletion of primary minerals and subsequent accumulation of resistant and infertile secondary minerals (e.g., goethite, hematite, quartz) can result in severe nutrient deficiencies. In tropical sandy soils, the continued reliance on the BCSR method becomes increasingly ineffective and economically unsustainable without addressing the underlying CEC limitations. Alva (2006), Ho et al (2019), and Katagiri et al. (1991) observed that the primary factor that must be managed firstly in sandy soils is CEC by adding organic materials. Amending soils with organic material would increase CEC, consequently increasing nutrient retention.

The BCSR and SLAN methods are more focused on interpreting exchangeable base cations. However, both methods lack comprehensive combinations of all soil characteristics in determining the final status of soil fertility. The BCSR method is solely based on cation ratios without further knowing their absolute concentration. This approach, hence, limits its ability to determine a more nuanced understanding concerning the actual magnitude of the cation that is required by the plant. In contrast, clearer values are designated by SLAN method generating an easier improvement plan to achieve nutrient adequacy (Anda et al. 2012; Chaganti and Culman 2017; Koppitke and Menzies 2007; Sabudu et al. 2021). Furthermore, the differences in results between the national BCSR and SLAN methods with international standard were due to the different ranges of criteria. The BCSR method showed divergent outcomes based on the range of values used to express fertility status, with national scale values being more restrictive than international criteria (Tables 2 and 3). The latter was generally based on plant and soil tests in subtropical climates (Chaganti and Culman 2017; Koppitke and Menzies 2007), while the national criteria (PPT 1983) were determined based on Indonesian tropical soil. These stricter criteria are seemingly applied to offset an accelerated soil degradation rates across Indonesian humid tropic soils as intensive mineral weathering, acidifications and nutrient leaching are prevalent to occur.

Despite its apparent advantages, the Indonesian SLAN method is still considered prone to the variation of optimum ranges across all soil types, as well as may be less informative regarding cation competition in soil containing high Ca and Mg, *i.e.,* calcitic, dolomitic, and serpentinite soils, soils with high nutrient-fixation rates, *e.g.,* andic, vertic, and oxic soils, or high-leaching rate soils like sandy-textured or psammitic soils. The FMSCP method is considered more comprehensive owing to the involvement of organic matter and soil exchange parameters into its approach, which can be used as proxies for potential more holistic improvement. In the case of sandy soils at our studied transect, applying FMSCP is better than BCSR, but still highly cost farmers in maintaining cations above critical levels. While the BCSR and SLAN methods are simpler, they are not always efficient in interpreting soil fertility in various tropical soil types, therefore, should be combined to other approaches (*e.g.,* FMSCP, buildup and maintenance approach; Chaganti and Culman 2017; Olson et al. 1987).

CONCLUSIONS

The research transect comprised various soil types developed from diverse parent materials and topography in close proximity, exhibiting profound enrichment at the soil surfaces. The soil fertility status is low according to the FMSCP method. Meanwhile, the soil fertility status varied from balanced to excessive evaluated using BCSR method. National/Indonesian SLAN assessment revealed that all studied soils were deficient, while deficient to excessive statuses were found after being assessed using a more relaxed international standard. The BCSR and SLAN methods showed a significant relationship between slope gradient and soil parent material variations, resulting in substantial differences when assessed using the multivariate method. FMSCP is the recommended method for evaluating soil fertility status in the studied transect, highlighting its comprehensive approach as well as the sandy-textured and low CEC of all studied soils. The SLAN and BCSR approaches are recommended to be integrated into current fertility evaluation approach.

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