

Soil properties across land mapping units under upland rice shifting cultivation in West Papua, Indonesia

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ABSTRACT

Shifting cultivation remains widely practiced across tropical regions and has been implicated in soil degradation processes and broader environmental change. This research examines and analyzes the main soil properties of upland rice at harvest in shifting cultivation locations. Soil samples were collected from nine land mapping units (LMUs) representing shifting cultivation systems of upland rice in the harvest phase. The analyzed soil properties included texture, pH, soil organic carbon (C-organic), total nitrogen (N), available phosphorus (P), exchangeable cations (Ca^{2+} , Mg^{2+} , and K^{+}), cation exchange capacity (CEC), and base saturation (BS). Data were analyzed using descriptive statistics, boxplot visualization, and the Kruskal-Wallis test. The results indicate that soils at the study site are generally acidic, with low to moderate levels of soil organic carbon, total nitrogen, available phosphorus, exchangeable base cations, and cation exchange capacity, while base saturation is very low to low. Soil texture ranged from sandy to clayey, which influenced nutrient retention capacity and cation exchange characteristics. Boxplot analysis revealed substantial variability within LMUs, reflecting fine-scale spatial heterogeneity. However, the Kruskal-Wallis test indicated that most soil properties did not differ significantly among LMUs ($p > 0.05$), suggesting relatively homogeneous soil conditions at the landscape scale. Therefore, sustainable land management in shifting cultivation systems needs to integrate a conservation approach at the landscape scale with site-specific management to maintain soil fertility and the sustainability of land ecological functions.

Keywords: soil fertility, swidden agriculture, landscape, Arfak Tribe.

INTRODUCTION

Agricultural land is an important natural resource that supports global food security. The continued supportive measure also comes as the population rises, consequently, flexible food production puts more strain on agricultural land availability (Lanz et al., 2018; Onyutha, 2019). But due to changes in land-use, urbanization, and the impacts of climate change, productive agricultural land is declining globally (Creutzig et al., 2019). Under these conditions, communities in many tropical regions continue to rely on shifting cultivation as a survival

strategy. This system has long been practiced by rural communities, especially in hilly and mountainous areas, where natural vegetation is cleared through slash-and-burn methods, and the land is cultivated for a certain period before being left fallow to recover. In recent years, land-clearing activities using slash-and-burn methods have increased in line with the growing land needs of communities (Chen et al., 2023; Ying et al., 2018). Shifting cultivation is widespread in Asia, Africa, and Central and South America, with an estimated area of 280 million hectares, and is projected to continue in the future (Heinimann et al., 2017).

Shifting cultivation or swidden agriculture is often regarded as a major cause of deforestation and land degradation, particularly because forest clearing can increase surface runoff and accelerate soil erosion (Curtis et al., 2018; Hattori et al., 2019; Wang et al., 2023), and air pollution during the biomass burning phase (Nonglait et al., 2026). This practice involves clearing and burning forest vegetation during the dry season, followed by planting at the beginning of the rainy season. The land is then actively managed, including weed control, for several years before being returned to forest conditions through a period of fallow. However, several studies suggest that this system is also shaped by local knowledge that contributes to environmental sustainability, such as the careful selection of land-clearing sites, management of fallow periods, and practice of crop diversification (Taberima et al., 2020; Tapi et al., 2020; Thet and Tokuchi, 2020). Several studies have indicated that shifting cultivation affects the physical, chemical, and biological properties of soil. These changes include increased soil temperature, reduced moisture, and variations in nutrient content, such as carbon, nitrogen, and phosphorus, which are influenced by land-use cycles and the duration of fallow periods (Baul et al., 2023; Mukul and Herbohn, 2016; Temjen et al., 2022; Thokchom et al., 2023). Additionally, biomass burning activities impact soil microbial dynamics (Arunrat et al., 2024).

The Warmare District is an important upland rice production area managed by the Arfak community. The initial crop planted on land prepared using shifting cultivation systems is upland rice. These crops have been developed through the gradual involvement of Arfak farmers after migrants arrived in Papua from outside between 1972 and the present, and have been cultivated for generations by the Arfak people. These farmers are local residents of one of the major ethnic groups in Manokwari, the Arfak people, who rely on the shifting cultivation system to ensure their families' food security. The shifting cultivation practices carried out by the Arfak community in the vicinity of lowland tropical rainforests are based on the concept of *igya ser hanjob*, a local wisdom for sustainably managing agricultural land (Ataribaba et al., 2020; Tapi et al., 2020). However, this local wisdom is increasingly being challenged by socio-ecological changes that raise the risk of land

degradation (Krisnawati and Raya, 2025). This sustainability system is currently under threat from increased oil palm planting, infrastructure development, improved road access, and a growing population. However, they can accelerate land-use change and reduce fallow duration. Research (Tola et al., 2025), indicates that during the 2023–2024 period, shifting cultivation sites for upland rice were distributed across newly cleared areas, ranging from village peripheries to secondary forest zones, with topographic conditions ranging from flat to hilly and mountainous. Shifting cultivation is spatially distributed and uses land primarily according to the customary land rights of local indigenous communities, with an average area of 0.6 to 0.7 ha. These conditions indicate that the traditional shifting cultivation system remains integral to the landscape mosaic of indigenous lands amid intensifying pressure from large-scale land-use changes. There is also a need for information on soil-related land features in shifting cultivation to support sustainable land use and long-term food security. This circumstance emphasizes the need to evaluate soil properties in response to the impacts of changing patterns in shifting cultivation practices. Therefore, this study aimed to evaluate the soil properties of upland rice shifting cultivation in the harvest phase and their implications for sustainable land management in West Papua, Indonesia.

MATERIAL AND METHODS

Study area

Warmare District is one of the districts located in Manokwari Regency. This area was selected for the study due to a form of local wisdom-specifically, the practice of shifting cultivation for upland rice-that has been passed down through generations within the village communities. The study area encompasses approximately 10,367 hectares distributed across several villages, including Guentuy, Tanah Merah, Imboisrati, Sraindebey, Warmare 1, Warmare, Dindey, Duwin, Njuar, Umcen, Meny Satu, Meny, and Sotea. These villages were chosen based on the identified presence of shifting cultivation activities for upland rice carried out by the Arfak people, the region's indigenous inhabitants. The study location is shown in Figure 1.



Figure 1. Location of the study area

Material, method and analysis

The materials used in this study consisted of primary and secondary data sources. The primary data included: (1) drone-based remote sensing data acquired in 2025, capturing upland rice shifting cultivation during the harvest phase, and (2) soil data for each land mapping unit (LMU), obtained through soil sampling at a depth of 0–30 cm. Secondary data include: (1) LMU maps. LMUs were derived using a 1:50,000 soil map from the Center for Standard Testing of Agricultural Land Resources Instruments, Ministry of Agriculture, Indonesia, and (2) climate data records from 2015 to 2024. The equipment used included a Mavic 3M drone, GPS devices, and a soil auger.

Research procedures included: (1) A field survey was conducted to understand the spatial distribution of upland rice based on accessibility; (2) Aerial imaging using a drone, involving a preparation phase that includes selecting flight locations, planning flight paths, setting flight altitude, and determining image overlap (80% frontal overlap and 70% side-lap); (3) Drone image processing using Agisoft Metashape; (4) Spatial analysis of shifting cultivation land was carried out using QGIS 3.44.11; (5) Image interpretation via visual analysis to identify upland rice fields managed under the shifting cultivation system of

the local Arfak tribe; (6) Field verification (ground check) was conducted in collaboration with local farmers to validate the interpretation results; (7) Soil sampling at upland rice sites during harvest within shifting cultivation areas based on land management units (LMUs). Samples were collected from the 0–30 cm depth using a soil auger. At each site, multiple subsamples were combined into a single representative sample. Sampling locations were selected based on LMU distribution, accessibility, and the presence of upland rice cultivation. In total, 27 sampling sites were established across the LMUs (Figure 2). All samples were analyzed at the Soil Chemistry and Fertility Laboratory, Hasanuddin University.

Analysis method were applied: (1) The remote sensing method applied is Unmanned Aerial Vehicle (UAV)-based photogrammetry, combined with spatial analysis using GIS; and (2) Statistical analysis consisted of descriptive statistics (mean, standard deviation, and coefficient of variation) calculated for each soil parameter. Boxplots were used to visualize the distribution and variability of soil properties across the land mapping units. Owing to unequal sample sizes and non-normal data distribution, the Kruskal–Wallis test was applied to assess differences among LMUs. All analyses were performed using jamovi version 2.6.

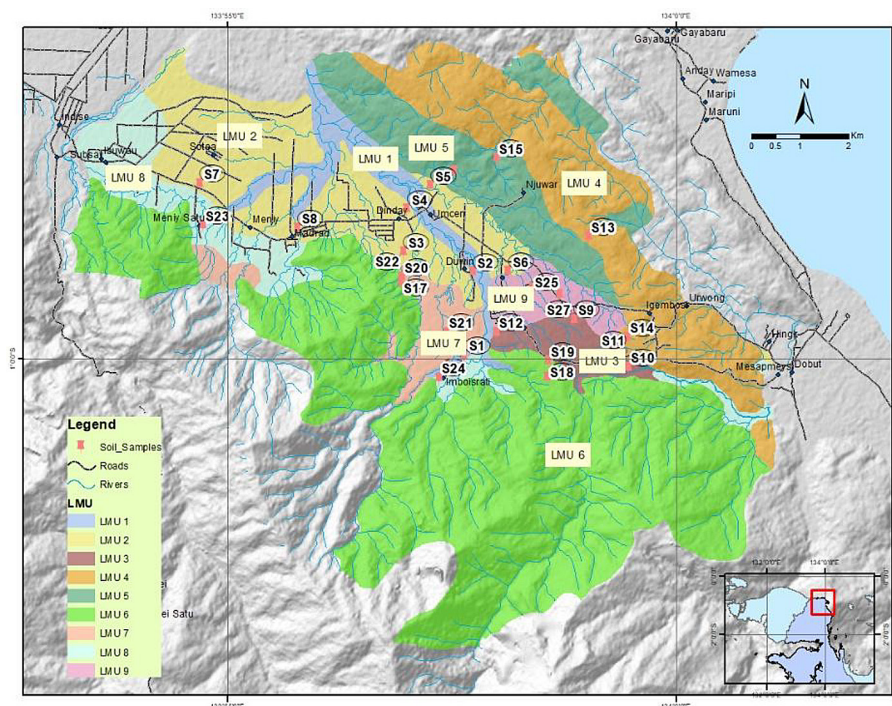


Figure 2. Distribution of soil sampling points across land mapping units (LMUs)

RESULTS AND DISCUSSION

Landform characteristics of each land mapping unit

The study area comprises a diverse range of landforms, including braided river floodplains, alluvial fans (head and middle sections), interhill plains, karst hills, tectonic hills, and volcanic intrusion landforms. This geomorphological diversity reflects variations in landform development, parent materials, topography, and hydrological conditions, which form the basis for delineating the Land Mapping Units (LMUs). LMU 1 is situated on a braided river floodplain characterized by relatively flat relief. LMUs 2 and 9 are located on the middle section of the alluvial fan, whereas LMUs 7 and 8 occur on the head of the alluvial fan, exhibiting relatively flat to undulating relief. LMU 3 is located on an interhill plain with relatively flat relief. Meanwhile, LMUs 4, 5, and 6 are developed on karst hill, tectonic hill, and volcanic intrusion landforms, respectively, and are characterized by hilly relief. These variations in geomorphological characteristics are expected to influence soil-forming processes through differences in parent materials, weathering intensity, sediment deposition, drainage conditions, and soil profile development. Consequently, these

factors are likely to contribute to the spatial variability of soil properties among the different LMUs. Shifting cultivation activities across different landforms and Land Mapping Units are presented in Figure 3.

Climatic conditions at the study area

Climate data for the study area for 2015–2024 period were obtained from the Meteorology, Climatology, and Geophysics Agency (BMKG) of West Papua, Indonesia. The study area has relatively high annual rainfall, approximately 2,312.6 mm year⁻¹, with an average monthly rainfall of around 192.7 mm with a range of 83.2 mm (October) – 366.2 mm (December). The district further has a mean temperature of 27.8 °C (range of 27.3–28.3 °C) and relative humidity of 82.1% with a range of 79.8–84.0% (Figure 4).

Farmers have long practiced traditional shifting cultivation, designating September (the “minor season”) and October (the “major season”) as the times for planting upland rice. Land preparation, including forest opening, clearing the forest floor, felling trees of various sizes, and burning biomass, takes one to two months, depending on the size of the plot. The upland rice harvest occurs in March or April. These practices are rooted in local knowledge and form a consistent seasonal



Figure 3. Shifting cultivation activities of upland rice across different LMUs in the study area (Drone imagery, 2025)

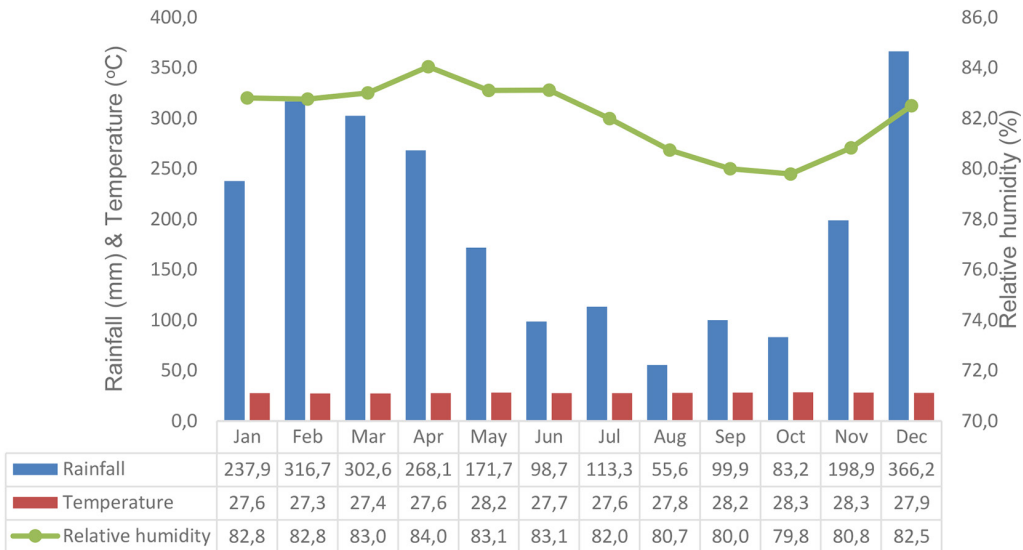


Figure 4. Mean annual rainfall, air temperature, and relative humidity, 2015–2024

cycle. However, based on ten years of climatic data for the study site, the upland rice planting period falls in September/October, classified as dry months (<100 mm of rainfall), while harvest occurs in March/April, classified as wet months

(>200 mm). Planting during the dry season hinders rice growth because water is scarce during early development. Conversely, harvesting during the wet season affects the drying and storage of the upland rice. Field observations revealed

that farmers do not mill their entire harvest at once; instead, they mill it gradually to meet the family's food needs.

Summary statistics of soil properties

Table 1 presents descriptive statistics for soil properties, including minimum, maximum, mean, median, standard deviation, and coefficient of variation. Soil texture is expressed as the relative proportions of sand, silt, and clay, while nine chemical properties were analysed: pH, organic carbon (C), total nitrogen (N), available phosphorus (P), exchangeable cations (Ca^{2+} , Mg^{2+} , and K^{+}), cation exchange capacity (CEC), and base saturation (BS). The statistical summary of soils in shifting cultivation fields during the harvest phase of upland rice cultivation is shown in Table 1.

Soil chemical property classifications followed Eviaty et al., (2023) and coefficient of variation (CV) classes followed Pandriadi et al., (2023). As shown in Table 1, soils were dominated by clay (37.4%), followed by sand (36.6%) and silt (26.1%). Soil pH ranged from 4.02 to 5.93 (mean 4.91), indicating strongly acidic to slightly acidic conditions. Organic carbon varied from 0.41% to 2.60% (mean 1.49%), while total nitrogen was generally low (0.05%–0.26%; mean 0.15%). Available phosphorus was also low to moderate (6.95–12.4 ppm; mean 10.4 ppm). Exchangeable Ca^{2+} , Mg^{2+} , and K^{+} were low (mean 2.96, 0.87, and 0.21 cmol(+)/kg, respectively), indicating poor base nutrient status. Organic matter ranged from 12% to 34% (mean 23.1%), classified as very low to low. Cation exchange capacity

(CEC) ranged from 15.9 to 21.0 cmol(+)/kg (mean 18.4), indicating low to moderate fertility.

Soil fertility was generally low, as indicated by strongly acidic pH and low levels of organic matter, total nitrogen, exchangeable base cations, and base saturation. Although the relatively high clay content may enhance water and nutrient retention, very low base saturation indicates limited availability of essential base nutrients for plant growth. Continued land clearing and biomass burning under shifting cultivation may further reduce organic matter and deplete soil nutrients over time. These findings highlight the need for sustainable land management to maintain soil functions and reduce environmental degradation.

Variability in soil properties reflects spatial heterogeneity across the study sites. Soil texture showed high variability, particularly for sand (CV = 56.83%), clay (CV = 48.40%), and silt (CV = 31.15%). Similarly, substantial variation was observed for soil organic carbon (CV = 54.36%), total nitrogen (CV = 40.00%), and Mg^{2+} (CV = 32.18%) (Table 1), likely reflecting differences in organic matter distribution, nutrient dynamics, and the combined effects of weathering and leaching in shifting cultivation systems. These patterns may also be influenced by fallow duration, burning intensity, and topography. Moderate variability was recorded for Ca^{2+} (CV = 29.39%), K^{+} (CV = 23.81%), and base saturation (CV = 24.68%), while low variability was observed for available phosphorus (CV = 12.21%), soil pH (CV = 9.16%), and cation exchange capacity (CV = 8.97%), indicating relatively uniform distribution across sites.

Table 1. Summary of descriptive statistics of soil properties of upland rice in the harvest phase in shifting cultivation

Parameter/ n=27	Min	Max	Mean	Median	Std. deviation	Coefficient of variation
Sand	3	87	36.6	33	20.8	56.83
Silt	5	43	26.1	27	8.13	31.15
Clay	8	79	37.4	33	18.1	48.40
pH (H_2O)	4.02	5.93	4.91	4.85	0.45	9.16
Organic C	0.41	2.60	1.49	1.48	0.81	54.36
Total nitrogen	0.05	0.26	0.15	0.12	0.06	40.00
Available P	6.95	12.4	10.4	10.4	1.27	12.21
Ca^{2+}	1,25	4,36	2,96	2,85	0,87	29.39
Mg^{2+}	0,36	1,82	0,87	0,85	0,28	32.18
K^{+}	0.12	0.33	0.21	0.21	0.05	23.81
CEC	15.9	21.0	18.4	18.1	1.65	8.97
BS	12	34	23.1	24	5.70	24.68

Forest conversion to shifting cultivation can either improve or degrade soil quality depending on management intensity and site conditions. In rice-based shifting cultivation systems, external fertilizer inputs are generally absent, so soil fertility depends on inherent nutrient reserves and inputs from biomass burning. (Abrell et al., 2024) report that such low-input systems, particularly under intensified cultivation cycles, may reduce soil fertility, including soil pH, organic carbon, total nitrogen, and exchangeable potassium. This spatial heterogeneity in soil fertility poses challenges for sustainable land management, as uniform management strategies are often ineffective.

SOIL PROPERTIES ACROSS LMU IN SHIFTING CULTIVATION SYSTEMS

Soil texture and chemical characteristics across each land management unit (LMU) at shifting cultivation sites during the upland rice harvest phase are presented in Tables 2 and 3. Mean values and variability of soil chemical properties across all LMUs are further summarized in Figure 5.

Table 2 shows that three soil texture classes were identified across the nine LMUs -clay, clay loam, and loamy sand-with clay being dominant. The highest clay content occurred in LMU 4, while the highest sand content was recorded in LMU 1. Clay- and loam-dominated soils may enhance water and nutrient retention, supporting plant growth and rice productivity through improved root–soil interactions (Zhao et al., 2021), whereas higher sand content reflects spatial variability driven by site-specific conditions. Soil texture patterns are also influenced by environmental and management factors.

Soil pH ranged from 4.52 to 5.25, indicating generally acidic conditions across the study area (Table 3). The highest mean pH was recorded in LMU 3 (5.25 ± 0.47), while the lowest occurred in LMU 7 (4.52 ± 0.31). Narrow ranges and low standard deviations suggest relatively homogeneous soil acidity across LMUs, as also shown by boxplot distributions (Figure 5a), where median pH ranged from 4.74 to 5.19. Slightly greater variability in LMU 4 and LMU 5 may reflect local differences in organic matter and leaching intensity. The acidic conditions are likely driven by intensive leaching in humid tropical environments, which depletes exchangeable base cations and promotes soil acidification. Although biomass burning in shifting cultivation can temporarily raise pH through base-rich ash inputs, this effect is short-lived under high rainfall conditions due to rapid leaching. (Arunrat et al., 2022) similarly reported short-term pH increases following burning, followed by gradual decline. Overall, the relatively uniform pH across LMUs suggests dominance of regional environmental controls and similar land management practices. Persistent acidity may limit productivity by reducing base cation availability and increasing Al^{3+} and Fe^{3+} solubility.

Soil organic carbon (SOC) ranged from 0.51% to 2.25%, corresponding to very low to moderate levels (Table 3). The highest SOC was recorded in LMU 9 ($2.25 \pm 0.40\%$), while the lowest occurred in LMU 4 ($0.51 \pm 0.14\%$). Boxplot analysis (Figure 5b) indicates substantial spatial variability across LMUs, with higher values in LMU 3 and LMU 9 and lower values in LMU 4 and LMU 7. Higher SOC in some LMUs may reflect greater litter inputs and vegetation cover, whereas lower SOC indicates limited organic

Table 2. Soil texture at upland rice in the harvest phase in shifting cultivation

LMU	N	Sand (%)	Silt (%)	Clay (%)	USDA texture
LMU 1	2	81.00 $\pm$ 8.49	9.50 $\pm$ 6.36	9.50 $\pm$ 2.12	Loamy sand
LMU 2	6	42.67 $\pm$ 8.36	28.50 $\pm$ 8.57	28.83 $\pm$ 2.93	Clay loam
LMU 3	4	39.50 $\pm$ 24.57	26.75 $\pm$ 8.06	33.75 $\pm$ 17.12	Clay loam
LMU 4	2	3.50 $\pm$ 0.71	17.50 $\pm$ 0.71	79.00 $\pm$ 0.00*	Clay
LMU 5	2	36.50 $\pm$ 24.75	23.50 $\pm$ 4.95	40.00 $\pm$ 29.70	Clay
LMU 6	3	29.00 $\pm$ 14.73	30.33 $\pm$ 5.69	40.67 $\pm$ 9.07	Clay
LMU 7	3	36.00 $\pm$ 10.44	29.67 $\pm$ 4.93	34.33 $\pm$ 5.51	Clay loam
LMU 8	2	35.50 $\pm$ 16.26	30.50 $\pm$ 6.36	34.00 $\pm$ 9.90	Clay loam
LMU 9	3	22.00 $\pm$ 11.53	27.67 $\pm$ 4.58	50.33 $\pm$ 11.85	Clay

Note: Values are mean $\pm$ SD; SD = 0 indicates no variability in the dataset.

Table 3. Soil chemical properties of upland rice fields in the harvest phase of shifting cultivation

LMUs	pH (H ₂ O)	Organic-C (%)	TN (%)	Available P (ppm)	Ca ²⁺	Mg ²⁺	K ⁺	CEC	BS (%)
					(cmol (+)/kg)				
LMU 1	5.19 ±0.11	1.68 ±1.30	0.15 ±0.10	9.56 ±0.21	3.86 ±0.55	0.88 ±0.18	0.15 ±0.04	17.20 ±0.93	29.00 ±2.83
LMU 2	5.05 ±0.19	1.60 ±0.67	0.15 ±0.05	10.57 ±1.11	2.55 ±1.08	0.88 ±0.14	0.20 ±0.04	19.24 ±1.42	19.50 ±4.85
LMU 3	5.25 ±0.47	1.94 ±0.84	0.18 ±0.07	9.88 ±1.62	2.77 ±0.43	0.58 ±0.09	0.25 ±0.07	17.68 ±2.14	21.75 ±4.92
LMU 4	4.98 ±1.35	0.51 ±0.14	0.07 ±0.02	10.23 ±1.24	4.20 ±0.23	0.95 ±0.15	0.22 ±0.01	17.38 ±0.50	32.00 ±2.83
LMU 5	4.75 ±0.89	1.12 ±0.98	0.11 ±0.08	11.42 ±1.37	2.97 ±0.16	0.90 ±0.08	0.18 ±0.01	16.11 ±0.13	26.50 ±0.71
LMU 6	4.77 ±0.05	1.36 ±0.91	0.15 ±0.06	9.59 ±2.35	3.36 ±1.00	1.03 ±0.07	0.23 ±0.02	18.42 ±2.09	26.00 ±5.57
LMU 7	4.52 ±0.31	0.80 ±0.22	0.10 ±0.02	10.94 ±1.15	3.38 ±0.61	1.03 ±0.26	0.26 ±0.06	19.04 ±0.84	25.00 ±2.65
LMU 8	4.78 ±0.07	1.44 ±1.24	0.16 ±0.07	11.01 ±0.23	2.54 ±0.45	0.69 ±0.09	0.24 ±0.00*	19.36 ±0.61	19.50 ±3.54
LMU 9	4.72 ±0.12	2.25 ±0.40	0.21 ±0.03	10.90 ±0.89	2.08 ±0.33	0.96 ±0.76	0.18 ±0.06	19.19 ±2.10	18.00 ±6.00

Note: Values are mean ± SD; SD = 0 indicates no variability in the dataset.

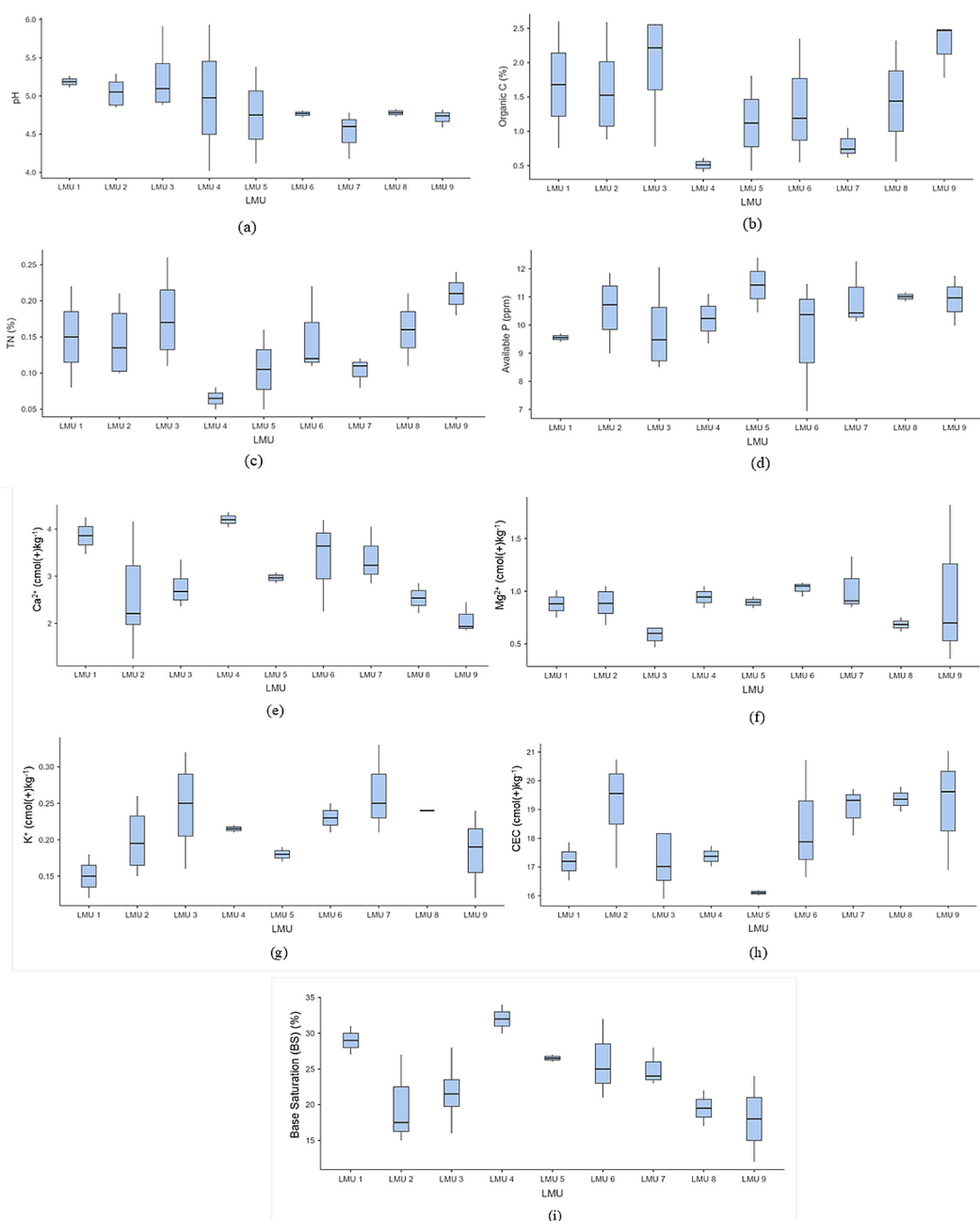


Figure 5. Boxplots of soil properties across LMUs: a) soil pH; (b) organic C; (c) total nitrogen (TN); (d) available P; (e) Ca²⁺; (f) Mg²⁺; (g) K⁺; (h) CEC; (i) BS

matter reserves typical of tropical soils with rapid decomposition after land clearing. Variability is likely driven by differences in biomass distribution, burning intensity, fallow duration, and land-use history. Although biomass burning may temporarily increase SOC inputs via ash, these effects are short-lived under humid conditions due to rapid decomposition and leaching (Arunrat et al., 2022; Baul et al., 2023). SOC values reported during the vegetative phase (1.5–2.1% in LMU 4) further suggest post-harvest declines due to plant uptake and continued organic matter decomposition (Panino et al., 2025).

Total nitrogen (TN) ranged from 0.07% to 0.21%, corresponding to very low to moderate fertility levels (Table 3). The highest value was recorded in LMU 9 ($0.21 \pm 0.03\%$), while the lowest occurred in LMU 4 ($0.07 \pm 0.02\%$). TN distribution closely followed soil organic carbon, indicating that nitrogen is mainly derived from organic matter decomposition. Boxplot analysis (Figure 5c) shows considerable variability across LMUs, with median TN values ranging from 0.065% to 0.210%. Higher SOC was associated with higher TN, confirming that organic matter mineralization is the primary nitrogen source in the absence of fertilizer inputs. Low TN in some LMUs reflects limited nitrogen reserves, potentially constraining soil fertility. This variability is driven by differences in biomass inputs and nitrogen losses through leaching and volatilization, which are common in humid tropical environments. Previous studies similarly show that TN dynamics in shifting cultivation are strongly controlled by organic matter availability and rapid nutrient cycling, with no major differences compared to post-burn or secondary forest systems (Arunrat et al., 2022; Terefe and Kim, 2020).

Available phosphorus (P) ranged from 9.56 to 11.42 ppm, corresponding to low to moderate fertility levels (Table 3). The highest value occurred in LMU 5 (11.42 ± 1.37 ppm), while the lowest was recorded in LMU 1 (9.56 ± 0.21 ppm). Overall, available P was relatively uniform across LMUs, with median values of 9.48–11.45 ppm (Figure 5d), indicating low spatial variability. This homogeneity suggests that P availability is mainly controlled by inherent soil properties rather than local management practices. In shifting cultivation systems, P inputs derive from organic matter mineralization and biomass burning ash, without external fertilization (Baul et al., 2023). However, P availability remains low due to strong

fixation by Fe, Al, and clay minerals under acidic conditions, consistent with the uniformly low soil pH across LMUs. Although biomass burning may temporarily increase P, such effects are generally short-lived and not significantly different among sites (Arunrat et al., 2022). Overall, phosphorus dynamics are governed primarily by soil acidity and inherent soil characteristics, making low P availability a key constraint on soil fertility in the study area.

Exchangeable base cations (Ca^{2+} , Mg^{2+} , and K^{+}) were generally low to moderate across the study sites (Table 3), indicating limited reserves of essential nutrients. Concentrations ranged from 2.08–4.20 cmol(+)/kg for Ca^{2+} , 0.58–1.03 cmol(+)/kg for Mg^{2+} , and 0.15–0.26 cmol(+)/kg for K^{+} , with the highest values recorded in LMU 4 (Ca^{2+}), LMU 6 (Mg^{2+}), and LMU 7 (K^{+}). Boxplot analysis (Figure 5e–5g) indicates generally low variability among LMUs, although Mg^{2+} showed relatively higher spatial variation. In shifting cultivation systems without fertilizer inputs, base cation availability depends mainly on mineral weathering and biomass burning ash. Although burning can temporarily increase cation levels, these are rapidly depleted under high rainfall due to leaching. Previous studies report no significant long-term effects of burning on Ca^{2+} , Mg^{2+} , and K^{+} (Arunrat et al., 2022). The decline in Mg^{2+} after forest conversion may also reflect biomass removal and reduced nutrient cycling (Baul et al., 2023). Overall, low base cation levels are strongly linked to acidic conditions and intensive leaching in humid tropical environments.

CEC ranged from 16.11 to 19.36 cmol(+)/kg, corresponding to low to moderate fertility classes (Table 3). The highest mean value occurred in LMU 8 (19.36 ± 0.61 cmol(+)/kg), while the lowest was in LMU 5 (16.11 ± 0.13 cmol(+)/kg). Low standard deviations and boxplot distributions (Figure 5h; median 16.1–19.6 cmol(+)/kg) indicate relatively uniform CEC across LMUs. This suggests a generally consistent cation retention capacity across the study area. However, soil fertility is limited more by low exchangeable base cations and organic matter than by CEC itself. The moderate CEC is likely driven by clay and organic matter content, which provide negative charges for cation retention (Solly et al., 2020; Suntoro et al., 2024). Despite this, strongly acidic conditions may reduce effective nutrient availability due to Al^{3+} and Fe^{3+} dominance on exchange sites. Overall, improving soil fertility in shifting cultivation

should prioritize increasing organic matter and replenishing base cations rather than CEC alone.

Base saturation (BS) ranged from 18.00% to 32.00%, corresponding to very low to low fertility status (Table 3). The highest mean occurred in LMU 4 ($32.00 \pm 2.83\%$), while the lowest was in LMU 9 ($18.00 \pm 6.00\%$). Low BS values indicate dominance of acidic cations (H^+ and Al^{3+}) on the exchange complex and limited availability of base cations, reflecting strongly acidic conditions across LMUs. Boxplot analysis (Figure 5i) shows median values of 17.5–32%, indicating moderate variability. Low BS is consistent with intensive leaching in wet tropical environments, leading to base cation depletion and reduced soil fertility in shifting cultivation systems. As BS represents the proportion of base cations relative to CEC, it is a key indicator of soil fertility (Kabala and Jedrzejewski, 2024), with low values reflecting acidic conditions and nutrient limitations (S. Zhang et al., 2023). Overall, low BS highlights acidic soil conditions and limited base cations as major constraints on fertility in the study area.

Statistical analysis: Kruskal-Wallis test

Kruskal-Wallis tests were performed to assess differences in key soil properties among land management units (LMUs), including sand, silt, and clay fractions; organic carbon; total nitrogen; available phosphorus; exchangeable cations; cation exchange capacity; and base saturation. The results are presented in Table 4. The Kruskal-Wallis test (Table 4) showed no significant differences ($p > 0.05$) among LMUs for most soil

properties, including pH, organic carbon, total nitrogen, available phosphorus, exchangeable Ca^{2+} , Mg^{2+} , K^+ , CEC, and base saturation. This indicates relatively homogeneous soil chemical conditions across the landscape, consistent with overlapping boxplot distributions (Figures 5a–5i). This homogeneity is likely driven by uniform environmental conditions, particularly high rainfall and associated leaching, as well as similar land management practices. In contrast, clay, sand, and base saturation showed marginal differences among LMUs (p-values approaching significance), suggesting that microscale factors such as biomass distribution, microtopography, and weathering still contribute to localized variability.

The study site lies in a wet tropical forest with high annual rainfall, near year-round precipitation, low temperature variability, and consistently high humidity (Figure 4). These climatic conditions strongly influence local shifting cultivation practices. Land preparation coincides with the low-rainfall season and involves vegetation clearing and biomass burning, while upland rice is planted at the onset of the rainy season. High rainfall enhances nutrient leaching, particularly of base cations, which may contribute to relatively homogeneous soil chemical properties across LMUs. Persistently high humidity and stable temperatures also promote organic matter decomposition and vegetation regrowth during the fallow period. Arunrat et al., (2022) reported that biomass burning primarily affects soil pH, with limited impacts on soil organic carbon, total nitrogen, phosphorus, and exchangeable cations. This may reflect nutrient uptake by upland rice during cultivation, which masks short-term changes in soil properties. These findings highlight the importance of the fallow period in maintaining soil fertility in shifting cultivation systems. The observed homogeneity of soil properties across LMUs suggests that wet tropical climate conditions and traditional management practices exert a stronger influence on soil fertility dynamics than local-scale variability.

Implications for soil fertility management in shifting cultivation systems

This study provides insights into soil fertility management in shifting cultivation systems. Site-specific management is essential for sustaining productivity and long-term system resilience. Traditional practices in the study area

Table 4. Kruskal-Wallis test results for soil properties in shifting cultivation sites

Parameter	Chi-Square (X^2)	df	p-value
Sand	13.58	8	0.093
Silt	10.89	8	0.208
Clay	15.50	8	0.050
pH (H_2O)	12.74	8	0.121
Organic C	10.48	8	0.233
Total N	10.44	8	0.235
Available P	5.43	8	0.711
Ca^{2+}	13.00	8	0.112
Mg^{2+}	13.31	8	0.102
K^+	9.83	8	0.277
CEC	10.17	8	0.253
BS	13.86	8	0.085

maintain ecological functions through fallow periods and the use of natural biomass, supporting nutrient cycling, soil recovery, and ecosystem stability. Based on these findings, this study proposes soil fertility management strategies tailored to local environmental conditions and community-based practices.

Organic matter input: Application of cover crops

Soil organic matter is essential for soil health and agricultural sustainability as it regulates nutrient availability, improves water retention, and contributes to carbon sequestration (J. Zhang et al., 2024; Xia et al., 2024). However, conversion of forests to shifting cultivation can significantly reduce soil organic carbon stocks, with losses of up to 54.40% (Tesfay et al., 2025). Maintaining soil organic matter is therefore critical for sustaining fertility in these systems. This can be achieved through organic inputs such as legume cover crops and crop residue mulching, which enhance organic matter, improve moisture retention, reduce nutrient leaching, and support long-term productivity.

Common leguminous cover crops at the study site include *Mucuna pruriens*, *Centrosema pubescens*, *Calopogonium* spp., *Pueraria phaseoloides*, *Arachis hypogaea*, *Vigna unguiculata*, *Glycine max*, *Vigna radiata*, and woody legumes

such as *Leucaena*, *Gliricidia*, *Sesbania*, and *Crotalaria* spp. These species improve soil fertility through biological nitrogen fixation, increasing nitrogen availability for subsequent crops. Their root exudates also enhance the solubilization of bound phosphorus and calcium compounds, improving nutrient availability and uptake (Koli et al., 2025). Overall, integrating these legumes into shifting cultivation can sustain soil fertility and reduce reliance on external inputs. It was found that all farmers in the study area used paddy straw from upland rice harvests as surface mulch, which they report helps suppress weeds and reduce runoff and erosion (Figure 6). However, straw decomposition may increase dissolved organic carbon losses through leaching (Park et al., 2021). In contrast, more labile amendments such as compost and manure are generally more effective than straw or biochar in increasing plant-available phosphorus, due to enhanced microbial activity and faster nutrient mineralization (Islam et al., 2026).

Crop rotation and diversification

Crop rotation involves sequential cultivation of different crops on the same land, with varying nutrient uptake and rooting depths that help disrupt pest and disease cycles and suppress weeds (Tanveer et al., 2019). In the study area, shifting cultivators practice crop rotation and

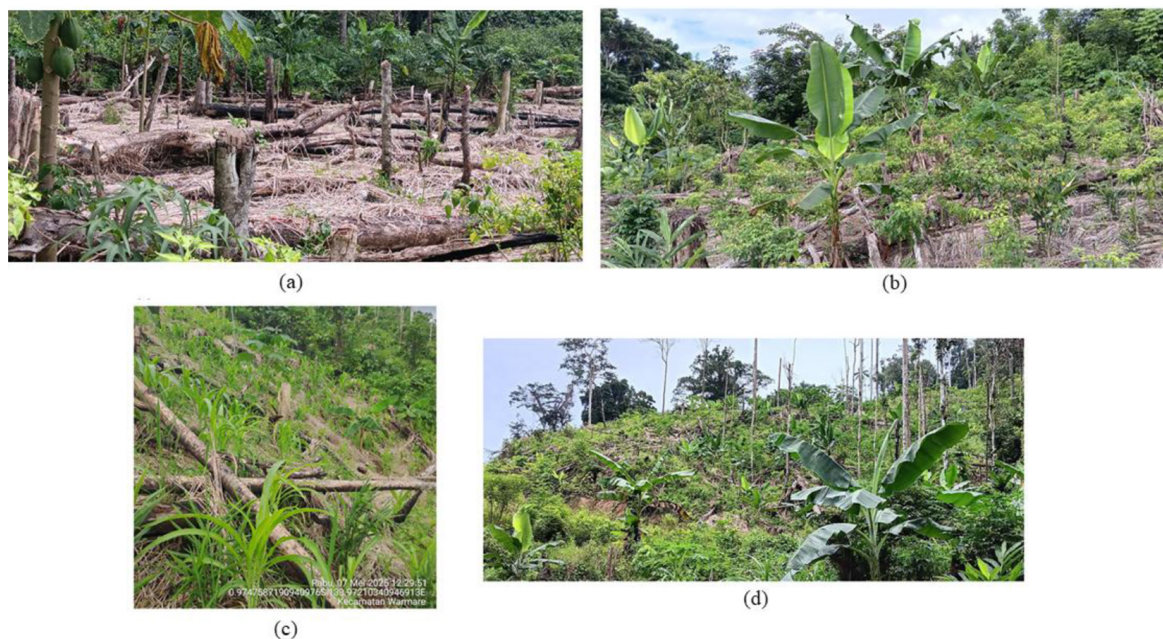


Figure 6. (a) Application of upland rice straw as mulch; (b) crop rotation to chili; (c) crop rotation to maize; (d) crop diversification following upland rice cultivation in shifting cultivation systems

diversification, typically planting upland rice first, followed by maize, vegetables, chili, tubers, and bananas. This diversified system improves land-use efficiency, reduces production risk, and supports household food security while helping maintain soil productivity and sustainable livelihoods. Shifting cultivators in the study area practice crop rotation and diversification, shifting from monoculture cereals to mixed cropping systems (Figure 6). These practices improve soil moisture retention and fertility, while reducing dependence on synthetic fertilizers and enhancing soil aggregate stability and microbial activity (Kim et al., 2025; Koli et al., 2025).

Management of the fallow period

The fallow phase is a key component of shifting cultivation, allowing soil fertility to recover through organic matter accumulation and nutrient cycling. Thus, reducing land-clearing frequency and ensuring adequate recovery time are essential for maintaining long-term productivity. In the study area, fallow duration before re-cultivation varies among farmers due to differences in land availability and management practices. Interviews indicated that fallow periods in the study area range from <5 to ~10 years. Farmers reported that continuous cultivation reduces soil fertility and rice yields while increasing pest and disease incidence, leading to intentional fallow management for soil recovery. Longer fallows promote vegetation regrowth and improve soil properties, including organic carbon, nitrogen, phosphorus, potassium, moisture, and microbial abundance, compared with younger fallows (<5 years) (Chetia et al., 2026; Sharma et al., 2022; Susanto, 2026).

Liming

Soil acidity in shifting cultivation systems can be mitigated through liming, which neutralizes hydrogen ions, raises soil pH, and improves crop productivity (S. Zhang et al., 2023). However, adoption remains limited due to financial constraints and limited technical knowledge. Interviews show that farmers rarely apply soil amendments such as lime, fertilizers, or pesticides during cultivation. Targeted support from agricultural agencies is therefore needed to improve access to amendments and provide technical guidance on liming practices. Targeted liming can improve soil chemical properties by raising

pH, increasing nutrient availability (particularly phosphorus), and reducing toxicity from acidity and Al^{3+} in acidic soils. Higher pH enhances nutrient accessibility and overall soil fertility. In addition, phosphate rock and microbial inoculants may improve pH, available N and P, and microbial biomass, while enhanced native microbial activity further supports phosphorus acquisition (Panino et al., 2025; Wapongnungsang et al., 2021). In Manokwari Regency, karst-derived limestone offers a local amendment source for acidity management; however, its effectiveness and feasibility require further evaluation under site-specific conditions.

Management of shifting cultivation in the study area is expected to become more challenging due to road development, improved accessibility, administrative expansion, and oil palm plantation growth. These drivers may accelerate land-use change and shorten fallow periods. Reduced fallow duration weakens soil recovery processes, increasing the risk of degradation and undermining long-term system sustainability. Supportive government policies and regulatory frameworks are needed to safeguard sustainable agricultural land at the study site, prioritizing ecological function, adequate fallow periods, and long-term system sustainability. Shifting cultivation is not only a food production system but also part of local knowledge and cultural heritage (Krisnawati and Raya, 2025; Tola et al., 2025), and it plays a key role in maintaining tropical landscape integrity and household food security.

CONCLUSIONS

This study shows although the study area exhibits diverse landscapes ranging from floodplains to tectonic hills and karst, most soil chemical properties do not differ significantly among LMUs. This suggests that due to the humid tropical climate of West Papua and the relatively similar practices of shifting agriculture, pedogenic processes and land management may exert a stronger influence on soil chemical characteristics than geomorphological differences alone. that soil properties in shifting cultivation systems in Warmare District do not differ significantly among land mapping units (LMUs). However, Kruskal–Wallis and boxplot analyses indicate strong microscale heterogeneity, with variability occurring mainly within rather than between

LMUs. These results suggest that shifting cultivation does not produce distinct soil conditions at the landscape scale. Soil pH was predominantly acidic, indicating limited nutrient availability and low soil fertility. Although some properties were relatively uniform across LMUs, variability within units suggests potential long-term constraints on soil quality. While similarity among LMUs supports landscape-scale management, within-LMU variation highlights the need for site-specific interventions.

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