

Dynamics of soil chemical properties along oil palm chronosequences and natural forests in Central Sulawesi, Indonesia

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Abstract: Land use conversion from tropical forests to oil palm plantations substantially impairs soil fertility, yet the trajectory of soil chemical change across successive plantation ages remains poorly understood. This study investigated changes in soil organic carbon (SOC), nutrient availability, cation exchange capacity (CEC), and micronutrient dynamics along a chronosequence comprising primary forest, secondary forest, and oil palm plantations aged 6, 8, 10, and 12 years in Central Sulawesi, Indonesia. SOC declined consistently following forest conversion and exhibited no meaningful recovery after 12 years of cultivation. Soil pH remained strongly acidic across all land-use categories, with progressive acidification becoming more pronounced in older plantation stands. Available phosphorus exhibited considerable spatial variability, largely governed by Fe-P interactions under acidic conditions, thereby constraining phosphorus use efficiency despite external fertilisation inputs. Exchangeable base cations, particularly Ca, accumulated progressively with advancing plantation age, yielding elevated base saturation values; however, this apparent improvement in chemical fertility was not accompanied by corresponding increases in SOC or CEC, the latter exhibiting a declining trend in older plantation soils, reflecting diminished nutrient retention capacity over time. Micronutrient analysis revealed progressive accumulation of Fe, Mn, and Cu in long-term plantation soils, suggesting potential micronutrient imbalance and phytotoxicity risks. Collectively, the chronosequence analysis indicates a discernible transition from biologically regulated forest soils to input-dependent plantation systems characterised by persistently low SOC, declining CEC, and imbalanced nutrient dynamics. These findings underscore that conventional oil palm management practices are insufficient to restore soil chemical quality and may predispose these systems to long-term degradation, necessitating the adoption of sustainable soil management strategies that prioritise the restoration of organic matter and enhanced nutrient use efficiency.

Keywords: tropical agroecosystem; forest ecosystem; soil degradation; long-term soil fertility; biogeochemical cycling; land conversion

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Land use change from natural forest ecosystems to intensive agricultural systems is widely recognised as a major driver of soil degradation and biogeochemical alteration in tropical regions. In Southeast Asia, particularly Indonesia, the rapid expansion of oil palm (*Elaeis guineensis* Jacq.) plantations has substantially transformed forested landscapes, including in Central Sulawesi. Although oil palm contributes significantly to global vegetable oil supply and regional economic development, its expansion has raised serious concerns regarding soil fertility decline, carbon loss, and long-term ecosystem sustainability. Empirical evidence suggests that conversion of forest to oil palm plantations can lead to substantial reductions in soil organic carbon (SOC), often associated with changes in litter inputs, soil disturbance, and increased mineralisation rates (Handayani et al. 2020, Laskar et al. 2020).

Soil organic carbon is a fundamental component of soil quality, regulating soil structure, aggregate stability, water retention, and microbial activity. In tropical agroecosystems, SOC is particularly vulnerable due to rapid decomposition under warm and humid conditions. Recent large-scale assessments in oil palm plantations have demonstrated that SOC levels are generally low (approximately 1.6–2 g/kg) and vary with plantation age, management intensity, and environmental factors (Golicz et al. 2025). Furthermore, long-term management practices, including fertiliser application and organic amendments, have been shown to significantly influence SOC dynamics and microbial communities, thereby affecting overall soil health and productivity (Hairiah et al. 2020, Hidayat et al. 2024).

In addition to carbon dynamics, nutrient availability – particularly nitrogen (N), phosphorus (P), and potassium (K) – is closely linked to soil organic matter turnover and cation exchange capacity (CEC), a key indicator of soil chemical fertility that reflects the soil's ability to retain and supply essential nutrients. Forest ecosystems typically maintain efficient nutrient cycling through continuous litter deposition and high biodiversity, whereas conversion to monoculture systems, such as oil palm, disrupts these processes, increasing reliance on external inputs and the risk of nutrient imbalances and leaching. This vulnerability is especially pronounced in highly weathered tropical soils such as Ultisols and Oxisols, which dominate many Indonesian landscapes, including Sulawesi, and are characterised by low inherent fertility, high acidity, and limited base saturation (Allen et al. 2015,

Kurniawan et al. 2018, Patrick and Michael 2023). Because CEC in such soils is largely governed by organic matter and variable-charge clay minerals, reductions in SOC following land-use change directly reduce CEC, thereby further increasing nutrient leaching and lowering fertiliser efficiency (Hairiah et al. 2020, Hidayat et al. 2024). This interdependence between SOC, nutrient availability, and CEC underscores the importance of evaluating these parameters simultaneously to understand soil fertility dynamics under different land-use systems.

The chronosequence approach, or space-for-time substitution, provides a robust framework for assessing temporal changes in soil properties across different stages of land-use development. Previous studies have shown that SOC and soil structural properties vary significantly along chronosequences, reflecting progressive changes in land management and ecosystem development (Laskar et al. 2020, Hidayat et al. 2024). In oil palm systems, chronosequence analysis enables evaluation of soil recovery or degradation trajectories across plantation ages without long-term monitoring. However, most existing studies are geographically limited (e.g., Malaysia and Sumatra) and often focus on single soil parameters, leaving a significant knowledge gap in the integrated assessment of SOC, nutrient availability, and CEC across oil palm chronosequences in comparison with primary and secondary forests, particularly in Central Sulawesi, a region characterised by diverse soil types, predominantly Ultisols and Oxisols, that respond differently to land-use change than soils in other tropical regions. Site-specific studies are therefore essential to improve understanding of soil fertility dynamics and to develop sustainable land management strategies (Ahmad et al. 2018, Golicz et al. 2025).

Based on these considerations, it is hypothesised that forest conversion to oil palm plantations leads to significant declines in SOC, nutrient availability, and CEC due to reduced organic matter inputs and altered nutrient cycling processes. However, these soil properties may show partial recovery or stabilisation with increasing plantation age, due to litter accumulation and management practices. Primary forest ecosystems are expected to maintain significantly higher levels of SOC, nutrient availability, and CEC than secondary forests and oil palm systems, reflecting their more stable, undisturbed ecological conditions.

The primary objective of this study is to evaluate the dynamics of soil chemical properties across oil palm plantations of varying ages, compared with primary and secondary forest ecosystems in Central Sulawesi, Indonesia. Specifically, this research aims to quantify SOC, nutrient availability (N, P, and K), and CEC, and assess how these parameters change along an oil palm chronosequence to contribute to the development of more effective soil management strategies for maintaining long-term soil fertility in tropical agroecosystems.

MATERIAL AND METHODS

Study area. This study was conducted in two sub-districts, Rio Pakava and Pinembani, in Donggala Regency, Central Sulawesi, Indonesia, at coordinates 1°17'42.73"S and 119°33'7.92"E. This region is dominated by highly weathered tropical soils, such as Ultisols and Oxisols. It has a humid tropical climate, with average annual rainfall of 1 500–2 000 mm and relatively stable year-round temperatures ranging from 24–28 °C, conditions that intensify mineral weathering and accelerate the dynamics of soil organic matter. The land-use systems examined in this study include oil palm (*Elaeis guineensis* Jacq.) plantations of varying ages, 6, 8, 10, and 12 years, with primary and secondary forest ecosystems serving as control groups. The topography of the observation points was as follows: primary forest, slope > 25%; secondary forest, slope 10–20%; 6-year-old oil palm plantations, slope 0–5%; 8-year-old oil palm plantations, slope 10–18%; 10-year-old oil palm plantations, slope 20%; and 12-year-old oil palm plantations, slope > 25%.

Research design and sampling strategy. This study employed a survey-based chronosequence approach to evaluate changes in soil chemical properties associated with oil palm plantation age. This approach facilitates the analysis of temporal dynamics by substituting space for time through comparisons across various locations with different land-use histories but relatively similar environmental conditions.

Sampling locations were selected using a purposive approach, taking into account the uniformity of soil-forming factors such as parent material, topography, and climate, to ensure that the observed variations were primarily attributable to differences in land use and oil palm age. For each land-use type (6-, 8-, 10-, and 12-year-old oil palm plantations, as well as primary and secondary forests), six samples were collected at depths of 0–40 cm, resulting in a total of 36 observation units analysed.

The parameters analysed were: soil pH using the EC (electrical conductivity) electrode method, organic carbon using the Walkley and Black method (Nelson and Sommers 1982), total nitrogen (Kjeldahl method), available phosphorus (Bray I method, adjusted to soil pH), exchangeable potassium (NH_4OAc extraction), cation exchange capacity (NH_4OAc extraction at pH 7), (Thomas 1982), meanwhile the Ca and Mg cations from the extraction were measured using an atomic absorption spectrometer (Shimadzu model AA-6300, Kyoto, Japan), while the K and Na cations were measured using a Flame Photometer (Cole-Parmer Dual-Channel model EW-02655-10, Vernon Hills, USA). Al-dd and H-dd in the soil were analysed following extraction with 1 mol/L KCl (Thomas 1982). All analyses followed standard soil laboratory procedures to ensure data accuracy and reproducibility.

RESULTS AND DISCUSSION

Patterns of change in macro-nutrient content across various land-use types. Secondary forests have significantly lower pH values (notation b) compared to the other groups, which do not differ significantly from one another (notation a). In general, soil pH values along this gradient range from 4.2 to 4.9 (Figure 1), which is classified as typical of the acidity found in tropical Ultisols/Inceptisols. These relatively stable pH patterns across land-use types are consistent with the findings of Rahman et al. (2018), who reported that forest soil pH ranges from 4.6 to 5.0, while that of oil palm plantations ranges from 4.6 to 5.8, indicating that pH variation resulting from land conversion is generally not very significant over a moderate chronosequence timeframe. However, another study (Toyibulah and Ananda 2025) found the opposite pattern: oil palm plantations had a lower pH (5.25) compared to primary forests (6.00) and logged-over forests (5.98), which is believed to result from the leaching of base cations, as well as the intensive application of acidic fertilisers (urea, KCl). On the other hand, Behera et al. (2020) reported that oil palm cultivation actually increases soil pH, electrical conductivity, and the concentrations of exchangeable Ca and Mg, as a result of routine liming and dolomite fertilisation. These three contrasting findings confirm that the direction of soil pH change depends heavily on land management practices, such as liming, the type of fertiliser used, and the application of empty oil palm fruit bunches, rather than solely on plant age.

The most consistent pattern is evident in the organic carbon graph (Figure 1): primary and secondary for-

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Mean $\pm$ SD of general soil properties and macronutrients by land use type (Tukey HSD Test, $\alpha = 0.05$)

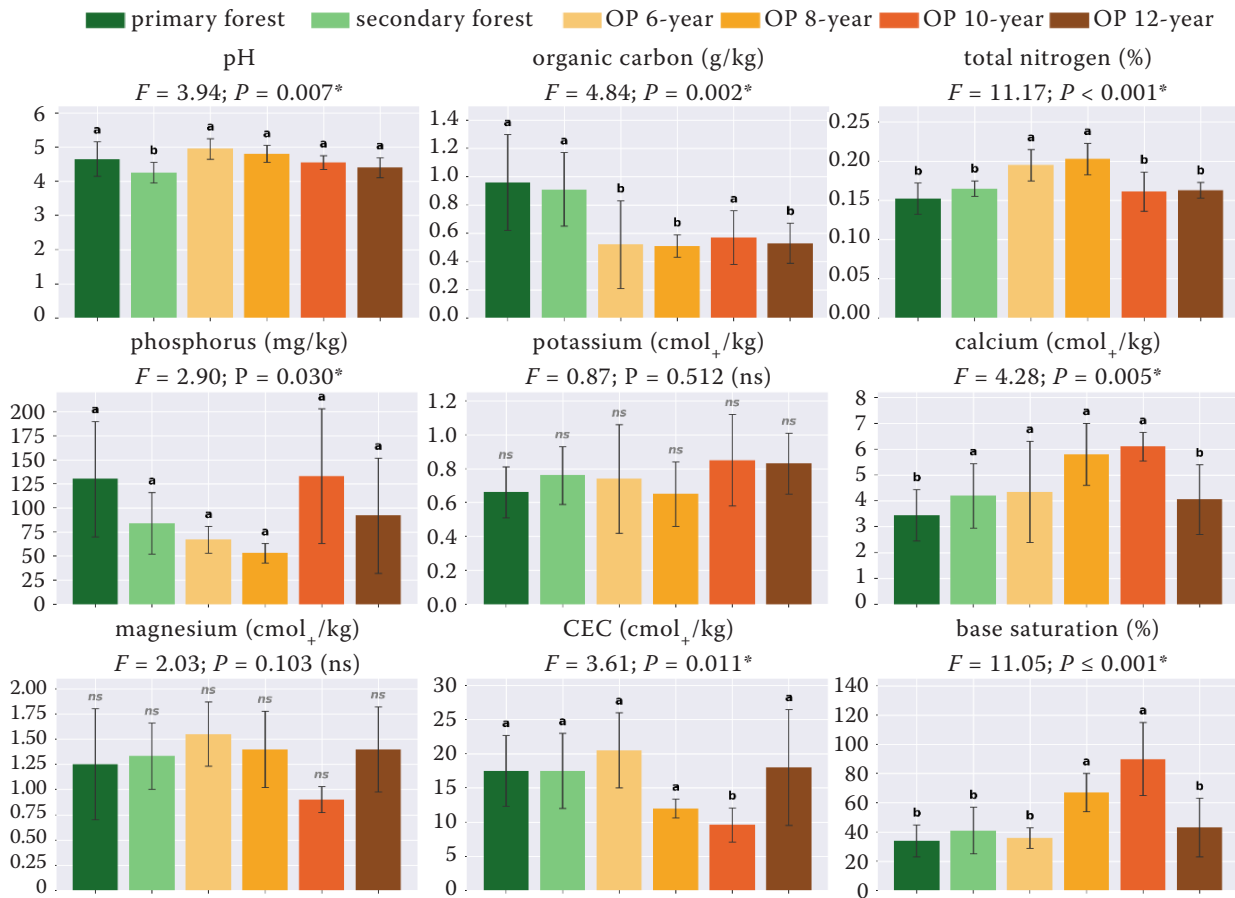


Figure 1. Results of the Tukey test for macronutrients across various land uses (primary forest, secondary forest, and oil palm plantations aged 6 to 12 years). CEC – cation exchange capacity

ests (a, ~ 0.9 – 1.0 g/kg) have significantly higher values than nearly all oil palm plantations (b, ~ 0.5 g/kg), except 10-year-old oil palm plantations (OP 10-year), which show slightly higher values. This finding is highly consistent with that of Guillaume et al. (2018). That cross-continental study (Peru, Cameroon, and Indonesia) showed that soil organic carbon stocks in oil palm plantations in Indonesia were approximately 14 ± 3 t C/ha lower than in natural forests. In Sumatra, the conversion of rainforest to oil palm plantations was found to result in total carbon losses of up to 174 t C/ha, with a portion of the loss (up to 21%) originating from the belowground pool, where soil organic matter continued to decline for up to a decade after conversion. A synthesis of data from six landscapes in Indonesia also shows a decrease in organic carbon concentration in the 0–30 cm soil layer, averaging 8–20% in oil palm plantations and other land-use systems compared to natural forests (Straaten et al. 2015).

Interestingly, not all studies found a permanent decline; research conducted at 20 Indonesian oil palm

plantations (155 plots) showed that the overall trend in soil carbon stocks at a depth of 0–30 cm was not significantly different from zero for oil palms originating from either forest or non-forest areas, with an initial decline followed by gradual recovery. This may explain why the 10-year-old OP in the graph has slightly higher organic carbon than the 6-, 8-, and 12-year-old Ops, likely due to the accumulation of fronds and empty fruit bunches in the frond stack zone, which begins to form midway through the planting cycle (Behera et al. 2020).

Total N content shows a unique pattern: primary and secondary forests (b) are actually lower than the 6- and 8-year-old OP plots (a), but the 10- and 12-year-old OP plots drop back down to group "b". This indicates the effect of intensive N fertilisation (urea) during the early- to mid-growth phase of oil palm. Studies on nitrogen cycling in Sumatra show that the conversion of forests and jungle rubber plantations into rubber and oil palm plantations reduces soil fertility, which in turn decreases micro-

bial biomass and the rate of NH_4^+ transformation; there is also a tendency toward a decrease in total nitrogen and cation exchange capacity in oil palm or rubber plantations compared to forests, although this is not always statistically significant (Guillaume et al. 2018). However, the pattern of increasing total nitrogen in 6–8-year-old oil palms shown in this graph more accurately reflects the direct effect of urea fertiliser routinely applied during the productive canopy formation phase, before levels decline again in older plants due to increased nitrogen export through the harvest of fresh fruit bunches (FFB) and leaching in acidic soils (Allen et al. 2015).

Regarding phosphorus nutrient content, although the calculated *F*-value was significant, the Tukey test indicated that all groups were labelled "a". This is a classic pattern in which ANOVA results are significant. Still, the Tukey test becomes overly conservative due to high variability (SD), particularly in the 10-year-old oil palm plantation (OP 10-year), which exhibited a very wide range of values. The pattern of high P levels in primary forest, followed by a sharp decline in 6–8-year-old plantations (OP 6–8 year), and then a rebound in 10–12-year-old plantations (OP 10–12 year), is highly consistent with the literature on P dynamics in acidic soils in oil palm plantations. P availability is severely limited in acidic soils because P is bound by Al and Fe; this condition results in low P levels in young oil palm plantations, before the cumulative application of P fertiliser (TSP/rock phosphate) effectively increases available P in the soil. A study in Kalimantan (Toyibulah and Ananda 2025) confirms that available P and potential K levels tend to increase with plant age due to the accumulation of P and K fertilisers. Behera et al. (2020) similarly confirmed that available P concentrations increase as plantations age, indicating the need for rational P management to prevent excessive accumulation.

The pattern observed for potassium content showed no significant differences among soil types (ns), although the average OP values at 10 and 12 years appeared numerically higher. This is consistent with the highly dynamic nature of K and its rapid leaching in tropical, slightly acidic, light clay soils, such that the variation among replicates (large SD) masked the differences among treatment means. The low total soil K content is thought to result from the acidic soil pH, which causes competition between K and Al or Fe for adsorption sites; this necessitates routine KCl fertilisation, while exchangeable K remains fluctuating and shows no consistent trend over time (Prabowo et al. 2023).

Meanwhile, the Ca concentration showed an interesting pattern, increasing from primary forest (b) to a peak at 8–10-year-old OP (a), then declining again at 12-year-old OP (b). This is highly consistent with the common practice of liming or dolomite fertilisation in productive oil palm plantations. The application of gypsum or kieserite as a source of Mg and Ca in acidic soils has been shown to gradually increase exchangeable Ca in line with the production needs of fruit bunches and to raise soil pH above approximately 5 by precipitating Al^{3+} as inert aluminium hydroxide. The decrease in Ca in the 12-year-old OP likely reflects Ca export *via* fresh fruit bunch (FFB) harvests that exceed fertiliser inputs during the mature generative phase, or changes in maintenance fertiliser rates for older plants (Ayanda et al. 2019).

Similar to potassium, magnesium also showed no significant differences across land-use types. This illustrates the classic antagonistic relationship among Mg, K, and Ca within the soil cation exchange system of oil palm plantations. High Ca saturation in the soil adsorption complex is the best predictor of leaf K response to KCl fertilisation, and excessive Mg input can actually induce K deficiency. It is this complex Ca-Mg-K interaction that renders Mg relatively stable (non-significant), even though Ca and K exhibit different patterns across plant ages (Dubos et al. 2017).

Cation exchange capacity in primary and secondary forests, as well as in 6- and 12-year-old oil palm plantations, was high (a) ($17\text{--}20\text{ cmol}_+/kg$), whereas it decreased significantly in 8- and 10-year-old oil palm plantations (b) ($\sim 10\text{--}12\text{ cmol}_+/kg$). This U-shaped pattern aligns with the decline in organic carbon, which also occurs most sharply within the same age range, as organic matter is the primary contributor to the negative charge in tropical acidic mineral soils. The reported decline in organic carbon and effective cation exchange capacity (ECEC) in oil palm plantations relative to forests (Allen et al. 2015) reinforces the mechanistic link between organic matter loss and the decrease in cation exchange capacity during the mid-phase of the crop cycle, before it recovers in the 12-year-old OP, likely due to the accumulation of frond litter and empty fruit bunches during those years.

Base saturation exhibits the sharpest pattern in the graph: 8- and 10-year-old OP (a, 68–90%) are significantly higher than primary forest, secondary forest, 6-year-old OP, and 12-year-old OP (b, 34–60%). Toyibulah and Ananda (2025) reported a similar non-linear pattern, in which base satura-

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tion in 6-year-old oil palm plantations was around 13.7–13.8%, but actually decreased to only 4.6–7.0% at 15 years of age due to continuously declining pH and base leaching that exceeded fertiliser inputs. Meanwhile, Behera et al. (2020) showed that base saturation actually increased with intensive lime/dolomite application during the productive years. The peak in BS at 8–10 years of productive age in this graph most likely reflects the period of most intensive Ca-Mg fertilisation (dolomite/kieserite), before a reduction in maintenance doses for older plants (12-year-old OP) caused BS to drop again, approaching forest levels.

Patterns of change in micronutrient content across various land-use types. The most striking pattern in Fe content was observed in the 6-year-old OP treatment, which showed a sharp increase (a, ~4 750 mg/kg) nearly three times that of the other groups, all of which fell within a single homogeneous range (b, ~1 500–2 900 mg/kg), including primary and secondary forests (Figure 2). The surge in Fe in the 6-year-old OP is highly consistent with the

fundamental principles of acidic soil chemistry. Hussaina et al. (2021) confirmed that the low pH of acidic soils increases the solubility of elements such as Zn, Mn, Fe, and Al, which can trigger rapid accumulation, even to toxic levels. A similar principle is explained by Wala et al. (2021): soil acidification increases the availability of cations such as Al, Cu, Fe, Mn, and Zn due to the desorption of these elements from soil particles and their dissolution from minerals, in contrast to Mg and Ca, whose levels do not increase. The early phase of oil palm land clearing (6 years) is generally characterised by soil structure disturbance, compaction from heavy machinery, and accelerated decomposition of iron-manganese oxides due to changes in aeration and drainage regimes. Consequently, dissolved Fe levels surge before gradually stabilising again in older plants as soil structure recovers and the canopy closes.

Mn has a very high calculated *F*-value, with four distinct groups: secondary forest has the lowest value (d, ~7 mg/kg), followed by primary forest, 8-year-old OP, and 12-year-old OP (c, 27–48 mg/kg);

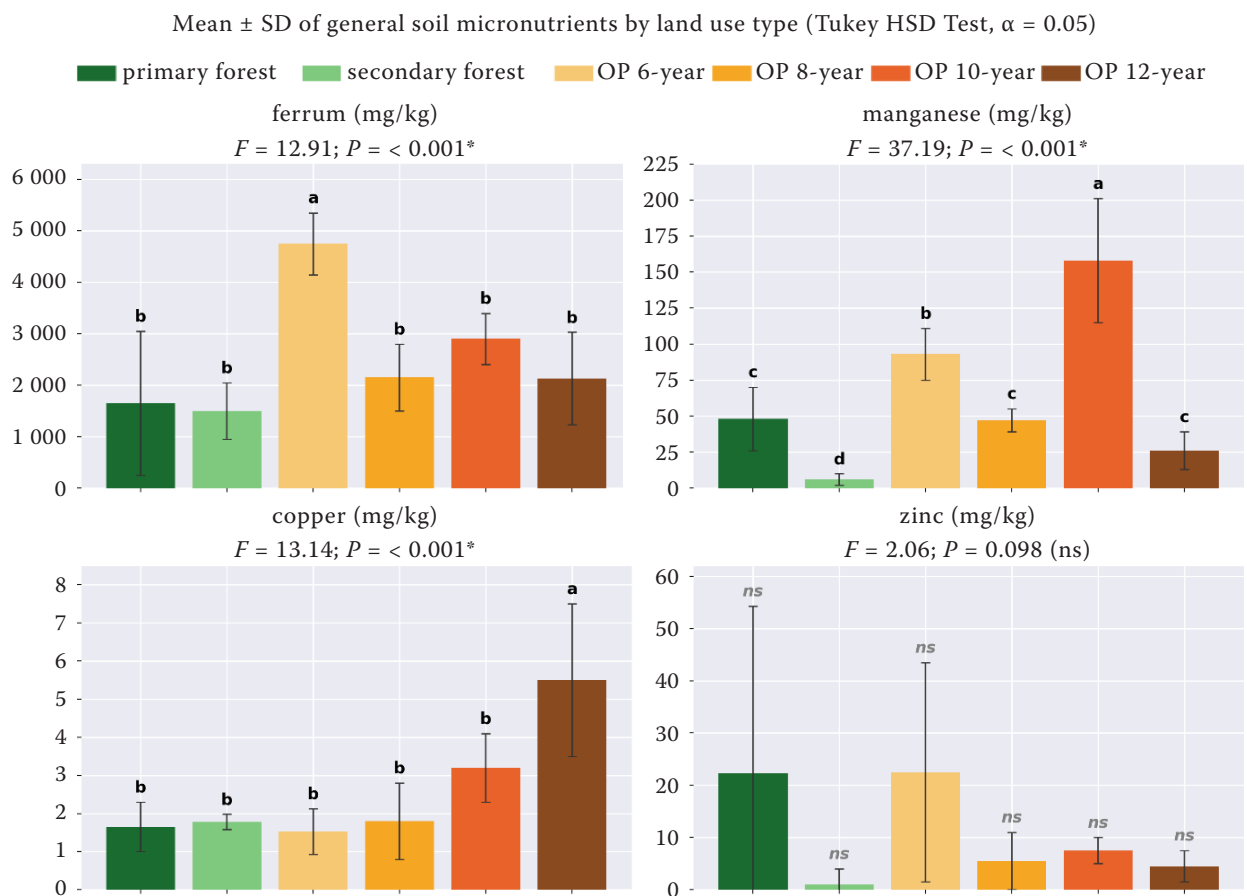


Figure 2. Results of the Tukey test for micronutrients across various land uses (primary forest, secondary forest, and oil palm plantations aged 6 to 12 years)

6-year-old OP (b, ~93 mg/kg); and, finally, 10-year-old OP, which peaks (a, ~158 mg/kg). This inverted U-shaped pattern (a sharp increase in 6–10-year-old OP, followed by a decrease in 12-year-old OP) is consistent with Mn's high sensitivity to soil pH and redox status. Acidic soils with high Fe and Al oxide content often contain large amounts of soluble Mn, and plant growth can be inhibited when soluble Mn accumulates excessively in plant tissues. Husnain et al. (2021) confirmed that the solubility of Mn, Al, and Fe reaches a maximum at low pH. The extreme Mn values in the 10-year-old OP are likely related to a combination of a still-low pH (~4.6, based on the pH data in the previous graph) and organic matter residues that begin to decompose actively during the mid-phase of the crop cycle, increasing the release of reduced Mn^{2+} . The very low Mn levels in secondary forest are noteworthy as an anomaly that may be related to a history of specific land disturbances (e.g., past burning or topsoil erosion) and warrant further verification.

Unlike the patterns observed for Fe and Mn, Cu levels remained relatively stable and low from the primary forest stage through the 8-year-old OP (b, 1.5–1.8 mg/kg), increased in the 10-year-old OP, and reached a significant peak in the 12-year-old OP (a, ~5.5 mg/kg), showing a cumulative pattern as the plants aged. This pattern of progressive Cu accumulation with oil palm age is highly consistent with the literature on the accumulation of micronutrients from agrochemicals in Indonesian oil palm plantations. Thompson et al. (2023) showed that oil palm production on acidic and nutrient-poor soils in Southeast Asia, in addition to depleting organic carbon and plant nutrients, can also lead to the accumulation of trace elements, including Cu and Zn, due to the use of agrochemicals containing trace metals, such as phosphate fertilisers and copper-based fungicides. This makes perfect agronomic sense, as copper-based fungicides (e.g., copper oxychloride) are routinely used to control fungal diseases in oil palm, and their residues accumulate cumulatively in the topsoil over time, explaining why the highest copper levels were found in the oldest plantations (12-year-old OP).

Meanwhile, Zn showed no significant differences among land types, although primary forest and 6-year-old OP exhibited the highest mean (~22 mg/kg), accompanied by a very wide standard deviation (SD nearly as large as the mean). It was this high variability that caused the Tukey test to fail to detect differ-

ences, even though the calculated *F*-value was close to significance. This pattern of non-significance with extreme SD is commonly observed for Zn due to its strong susceptibility to antagonistic interactions with other nutrients, particularly P. A systematic review by Bagus et al. (2025) on oil palm nutrition found an antagonistic effect between Cu and P fertiliser application, and showed that phosphate fertiliser treatments can reduce Cu and Mn concentrations in oil palm leaves even while improving Fe uptake. Because the dosage and timing of P fertiliser application (TSP/rock phosphate) vary greatly among planting blocks in field practice, variation in Zn among replicates became very large, consistent with the general pattern reported by Choudhury et al. (2021) that the conversion of forests to agricultural land and plantations tends to reduce soil concentrations of Mn, Cu, and Zn compared to natural forests although in this case the magnitude of variability statistically masked this average trend.

Overall, the conversion of forests to oil palm plantations is driven by two opposing forces: natural degradation the loss of organic litter consistently reduces organic carbon, total nitrogen, and CEC, consistent with previous findings that forest conversion to commodity plantations reduces soil organic carbon by 8–20%, whereas agronomic interventions such as routine fertilisation (urea, TSP, KCl, dolomite) result in higher levels of P, K, Ca, and Mg in productive plantations aged 8–10 years compared to natural forests. This pattern is reinforced by the dynamics of micronutrients, which follow soil acidity: Fe and Mn surge during the early-to-mid conversion phase (6–10-year-old OP), when soil disturbance and low pH are at their peak, as acidity increases both their solubility and the risk of toxicity, while Cu accumulates progressively due to unwashed fungicide residues until the plants reach 12 years of age. These fluctuating patterns in P, Ca, base saturation, Fe, and Mn confirm that age-specific fertilisation schedules and rates, not merely the time elapsed since conversion, are the dominant influencing factors; therefore, oil palm plantation management must balance long-term restoration of organic fertility with control of the risk of Fe/Mn toxicity and Cu accumulation.

REFERENCES

- Ahmad A., Lopulisa C., Imran A.M., Baja S. (2018): Soil physico-chemical properties to evaluate soil degradation under different land use types in a high rainfall tropical region: a case study from

<https://doi.org/10.17221/206/2026-PSE>

- South Sulawesi, Indonesia. IOP Conference Series: Earth and Environmental Science, 157. 1st International Conference on Food Security and Sustainable Agriculture in The Tropics (IC-FSSAT) 24–25 October 2017, Sulawesi Selatan, Indonesia.
- Allen K., Corre M.D., Tjoa A., Veldkamp E. (2015): Soil nitrogen-cycling responses to conversion of lowland forests to oil palm and rubber plantations in Sumatra, Indonesia. *PLoS One*, 10: e0133325.
- Ayanda A.F., Jusop S., Ishak C.F., Othman R. (2019): Utilization of magnesium-rich synthetic gypsum as magnesium fertilizer for oil palm grown on acidic soil. *PLoS One*, 15: e0234045.
- Bagus I.A., Akhmad R., Saidy, Razie R., Purnomo J., Hermantoro, Suparyanto, Pardamean B.T. (2025): Systematic literature review of oil palm on sandy soils. *Communications in Mathematical Biology and Neuroscience*, 49: 1–22.
- Behera S.K., Shukla A.K., Suresh K., Manorama K., Mathur R.K., Kumar A., Harinarayana P., Prakash C., Tripathi A. (2020): Oil palm cultivation enhances soil pH, electrical conductivity, concentrations of exchangeable calcium, magnesium, and available sulfur and soil organic carbon content. *Land Degradation and Development*, 31: 2789–2803.
- Choudhury B.U., Ansari M.A., Chakraborty M., Meetei T.T. (2021): Effect of land-use change along altitudinal gradients on soil micronutrients in the mountain ecosystem of Indian (Eastern) Himalaya. *Scientific Reports*, 11: 14279.
- Dubos B., Baron V., Bonneau X., Flori A., Ollivier J. (2017): High soil calcium saturation limits use of leaf potassium diagnosis when KCl is applied in oil palm plantations. *Experimental Agriculture*, 54: 794–804.
- Golicz K., Cheak S.C., Jacobs S., Stoltenberg A.G., Safaei M., Kimura S.B., Breuer L., Wartenberg A. (2025): The older, the better: a comprehensive survey of soil organic carbon under commercial oil palm plantations. *Environmental Risk Assessment*, 197: 1–15.
- Guillaume T., Kotowska M.M., Hertel D., Knohl A., Krashevskaya V., Murtillaksono K., Scheu S., Kuzyakov Y. (2018): Carbon costs and benefits of Indonesian rainforest conversion to plantations. *Nature Communications*, 9: 2388.
- Hairiah K., Noordwijk M.V., Sari R.R., Saputra D.D., Widiyanto, Suprayogo D., Kurniawan S., Prayogo C., Gusli S. (2020): Soil carbon stocks in Indonesian (agro) forest transitions: compaction conceals lower carbon concentrations in standard accounting. *Agriculture, Ecosystems and Environment*, 294: 106879.
- Handayani I.P., Widiastuti H., Coyne M.S., Widawati S. (2020): Soil organic carbon fractions in oil palm management systems. IOP IOP Conference Series: Earth and Environmental Science, 583, 012006.
- Hidayat F., Pane R.D.P., Sapalina F., Listia E., Koga T., Winarna, Lubis M.E.S., Oshiro M., Sakai K., Utami S.N.H., Tashiro Y. (2024): Long-term application of organic matter improves soil properties and plant growth-promoting bacteria in soil communities of oil palm plantation. *Soil Science and Plant Nutrition*, 70: 393–405.
- Husnain A.G., Hussain I., Bakar A.I., Zafar A., Imran B.C., Zafar H., Danish D.S., Niazi H., Touseef M., Ali A.K., Tariq M., Yousuf H., Usama M. (2021): Influence of soil pH and microbes on mineral solubility and plant nutrition: a review. *International Journal of Agriculture and Biological Sciences*, 5: 71–81.
- Hussaina S., Mahmooda M.H., Akbera A.R., Iqbalb M.S. (2021): Alkaline and acidic soils pose problems for nutrient availability: mitigation strategies. In: Saud S., Fahad S., Wang D.P., Nawaz T. (eds.): *Sustainable Soil Chemistry and Plant Nutrition Innovations and Applications*. Amsterdam, Elsevier, 115–132. ISBN: 978-0-443-40584-6
- Kurniawan S., Corre M.D., Matson A.L., Bisping H.S., Utami S.R., Straaten O.V., Veldkamp E. (2018): Conversion of tropical forests to smallholder rubber and oil palm plantations impacts nutrient leaching losses and nutrient retention efficiency in highly weathered soils. *Biogeosciences*, 15: 5131–5154.
- Laskar S.Y., Sileshi G.W., Pathak K., Debnath N., Nath A.J., Yasmin K., Singnar P., Das A.K. (2020): Variations in soil organic carbon content with chronosequence, soil depth and aggregate size under shifting cultivation. *Science of the Total Environment*, 762: 143114.
- Nelson D.W., Sommers L.E. (1982): Total carbon, organic carbon, and organic matter. In: Page A.L., Miller R.H., Keeney D.R. (eds): *Method of Soil Analysis (Part 2) – Chemical and Microbial Properties*. 2nd Edition. American Society of Agronomy and Soil Science Society of America, 539–579.
- Patrick S., Michael (2023): The importance of sustainable management of acid soils in the humid tropics under climate change and the future research directions. *Ecofeminism and Climate Change*, 4: 29–40.
- Prabowo N.E., Foster H.L., Nelson P.N. (2023): Potassium and magnesium uptake and fertiliser use efficiency by oil palm at contrasting sites in Sumatra, Indonesia. *Nutrient Cycling in Agroecosystems*, 126: 263–278.
- Rahman N., Neergaard A., Magid J., van de Ven G.W.J., Giller K.E., Bruun T.B. (2018): Changes in soil organic carbon stocks after conversion from forest to oil palm plantations in Malaysian Borneo. *Environmental Research Letters*, 13: 105001.
- Straatena O., Correa M.D., Wolfa K., Tchienkouab M., Cuellar E., Matthews R.B., Veldkampa E. (2015): Conversion of lowland tropical forests to tree cashcrop plantations loses up to one-half of stored soil organic carbon. *Proceedings of the National Academy of Sciences*, 112: 32.
- Thomas G.W. (1982): Exchangeable cation. In: Page A.L., Miller R.H., Keeney D.R. (eds): *Method of Soil Analysis (Part 2) – Chemical and Microbial properties*. 2nd Edition. American Society of Agronomy and Soil Science Society of America, 159–179.
- Thompson H.M., Ariantiningih E., Muhammad S.A., Gaw S., Robinson B. (2023): Nutrients and contaminants in soils of current and former oil palm production systems from Indonesia. *Land*, 12: 2144.
- Toyibulah, Ananda (2025): Analysis of soil chemical property variations in oil palm plantations of different ages in part of Saliki village, Muara Badak District. *Journal of Agriprecision and Social Impact*, 2: 253–265.
- Wala M., Kołodziejek J., Mazur J., Cienkowska A. (2021): Reactions of two xeric-congeneric species of *Centaurea* (Asteraceae) to soils with different pH values and iron availability. *PeerJ*, 9: e12417.

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