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# Impact of Forest Fires on the Stability and Distribution of Soil Organic Matter Fractions in Agroforestry Systems

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**ABSTRACT**

*Forest fires pose a significant threat to soil ecosystems by reducing soil organic matter, which is essential for maintaining soil structure and fertility. While the effects of fire on soil physical properties have been widely studied, the relationships between POM fractions, soil biophysical properties, and vegetation remain poorly understood. This study evaluated POM content under different land-use systems in the UB Forest following fire and examined its relationships with litter production, canopy cover, bulk density, porosity, and soil texture. Three land-use systems were investigated: protected forest (HL0), unburned agroforestry (AF1), and burned agroforestry (AF2), at soil depths of 0–10 cm and 10–30 cm, with four replicates per treatment (24 samples). Data were analysed using ANOVA and correlation-regression analyses. Protected forest had the highest total POM content (5.20 g kg$^{-1}$), whereas burned agroforestry had the lowest (1.93 g kg$^{-1}$), with the coarse POM fraction showing the greatest sensitivity to fire. Fire reduced total POM by 35% in the 0–10 cm layer compared with the deeper soil layer. Total POM was positively correlated with canopy cover and porosity but negatively correlated with bulk density, while no significant relationship was found with litter production or soil texture. These findings highlight the importance of maintaining vegetation cover and enhancing soil organic matter for effective post-fire ecosystem restoration.*

## 1. INTRODUCTION

Forest fires have emerged as one of the most critical environmental challenges worldwide during the last decade, threatening ecosystem sustainability, agricultural productivity, and climate relisience. Beyond causing extensive vegetation loss and atmospheric carbon emissions, fires substantially alter the physical, chemical, and biological properties of soil that underpin ecosystem functions and agricultural land productivity. According to Bowman *et al.* (2020), forest fires have increased globally in both frequency and intensity as a result of climate changes and human activities. A report from Global Forest Watch (2023) show that Indonesia lost more than 2.8 million hectares of tree cover due to fires between 2001 and 2022, with the peak loss occurring in 2016. These disturbances not only threaten biodiversity and forest resources but also create significant challenges for land management, agricultural production systems, and ecosystem restoration efforts.

From the perspective of agricultural engineering and land resource management, post-fire soil degradation represents a major obstacle to sustainable land utilization. Fires alter soil organic matter (SOM), reduce nutrient availability, increase soil compaction, and modify water infiltration and retention processes that are essential for crop and vegetation growth. Another study by Elakiya *et al.* (2023) confirms that fires cause significant changes in soil organic matter (SOM) content, including a decrease in carbon and nitrogen fractions, as well as disruption to soil microbial balance. In general, changes in SOM characteristics post-fire are closely related to ecosystem stability, land productivity, and environmental resilience against further degradation. These changes affect nutrient availability, long-term carbon storage, soil structure, microbial community changes, and soil biogeochemical properties that are important for ecosystem recovery and land productivity (Li *et al.*, 2024; Salgado *et al.*, 2024). These impacts have important implications for agricultural practices, particularly in the development of soil rehabilitation technologies and sustainable agroforestry systems designed to restore ecosystem functions after fire disturbances.

The urgency of this issue is further emphasised by the impacts of fires on the ecological and economic aspects of communities surrounding forest areas. Fires result in a decline in soil physical and chemical quality, which in turn affects the soil's capacity to support vegetation growth. López-Martín *et al.* (2018) reported that intense fires cause the redistribution of organic carbon to the micro-aggregate fraction of the soil and an increase in inert carbon that is difficult to decompose. This has implications for a decrease in nutrient availability and the soil's capacity to store water, as well as a reduction in biological activity. From a socio-economic perspective, fires also reduce the income of communities dependent on non-timber forest products (Awirya *et al*., 2025). A study by Salgado *et al*. (2024) revealed that repeated fires progressively degrade soil quality through the loss of labile carbon, total nitrogen, and damage to soil structure. Therefore, in-depth research is needed that not only evaluates the direct impacts of fires but also examines the interrelationships between soil ecosystem components such as soil organic matter fractions, land cover, and soil physical parameters.

Recent advances in agricultural engineering emphasize the integration of soil quality assessment and ecological indicators to guide post-disturbance land management. Among these indicators, particulate organic matter (POM) is receiving increasing attention because it is the most active and sensitive fraction of soil organic matter, responding rapidly to environmental changes and management interventions. POM plays a fundamental role in nutrient cycling, aggregate formation, water retention, microbial activity, and carbon sequestration in tropical agroforestry systems, making it a valuable indicator for evaluating soil recovery processes and designing effective restoration strategies.

In non-burned agroforestry systems, continuous inputs from litterfall, root turnover, and diverse vegetation structures promote POM accumulation, resulting in improved soil quality and ecosystem functioning. In general, multi-strata agroforestry systems contain higher POM concentrations than monoculture systems due to greater biomass production and belowground carbon inputs (Cardinael *et al*., 2018). In contrast, fire disturbance can substantially reduce POM through the combustion of organic residues and the loss of labile carbon fractions, thereby decreasing soil resilience and slowing ecosystem recovery. To extend of POM depletion depends on post-fires vegetation regeneration, canopy cover, litter production and land management practices, with partially recovered agroforestry systems often exhibiting faster POM restoration than severely burned areas.

Previous studies have investigated soil physical and chemical properties in the UB Forest landscape, demonstrating that differences in land-use systems significantly influence soil bulk density, porosity, hydraulic conductivity, aggregate stability, and organic carbon (Siahaan & Kusuma, 2021). However, the effects of fire disturbance on soil organic matter fractions, particularly particulate organic matter (POM), remain insufficiently explored in this landscape, while Kurniawan *et al*. (2021) highlighted the role of agroforestry management on soil carbon stocks. The research by Franzluebbers (2024) shows that the coarse fraction of POM plays an important role in supporting microbial activity and water retention. However, there has been limited research specifically evaluating the relationship between the particulate fraction of soil organic matter (POM) and other soil biophysical characteristics in the context of fires. These studies tend to separate POM evaluation and other environmental variables such as canopy cover or litter production. Thus, there is an important research gap that needs to be addressed: how does POM relate to litter production, canopy cover, soil bulk density, texture, and porosity in various types of post-fire land cover?

Therefore, this study aims to: (1) evaluate POM content in various types of land cover in the agroforestry system post-fire, and (2) analyse the relationship between POM and litter production, canopy cover, and soil physical properties, including bulk density, texture, and porosity. This study is expected to contribute theoretically to the development of understanding regarding the dynamics of tropical SOC fractions post-fire disturbance, as well as provide a strong scientific basis for land restoration efforts and sustainable agroforestry management. The practical implications of this research include the development of evidence-based strategies for post-fire soil conservation and management. Furthermore, the results of this study are important for policymakers, forestry practitioners, and the scientific community interested in the recovery of tropical forest ecosystems vulnerable to fire.

## 2. MATERIALS AND METHODS

### 2.1. Study Area

This study was conducted from August to October 2024 in the UB Forest area (forest education of Universitas Brawijaya) or Special Purpose Forest Area (KHDTK) located in Sumbersari, Tawangargo village, Karangploso Subdistrict, Malang District, East Java (Figure 1). Specifically, the UB Forest Area is used for educational and research activities and is located within the watershed on the slopes of Mount Arjuno, where pine-coffee agroforestry is the dominant form of land use in this area. Geographically, it is located at coordinates 7º49'2" S – 7º51'26" S and 112º34'11" E – 112º 36'37" E. The average annual rainfall at the research site ranges from 1,900 to 2,000 mm year$^{-1}$, of which 80% occurs in the rainy season, with an average air temperature of approximately 27 °C, average canopy cover of approximately 65%, as well as elevation of the research site ranges from 700 to 1100 meters above sea level (m asl) (Fitch *et al*. 2022; Rowe *et al*., 2022; Fitra *et al*., 2024).

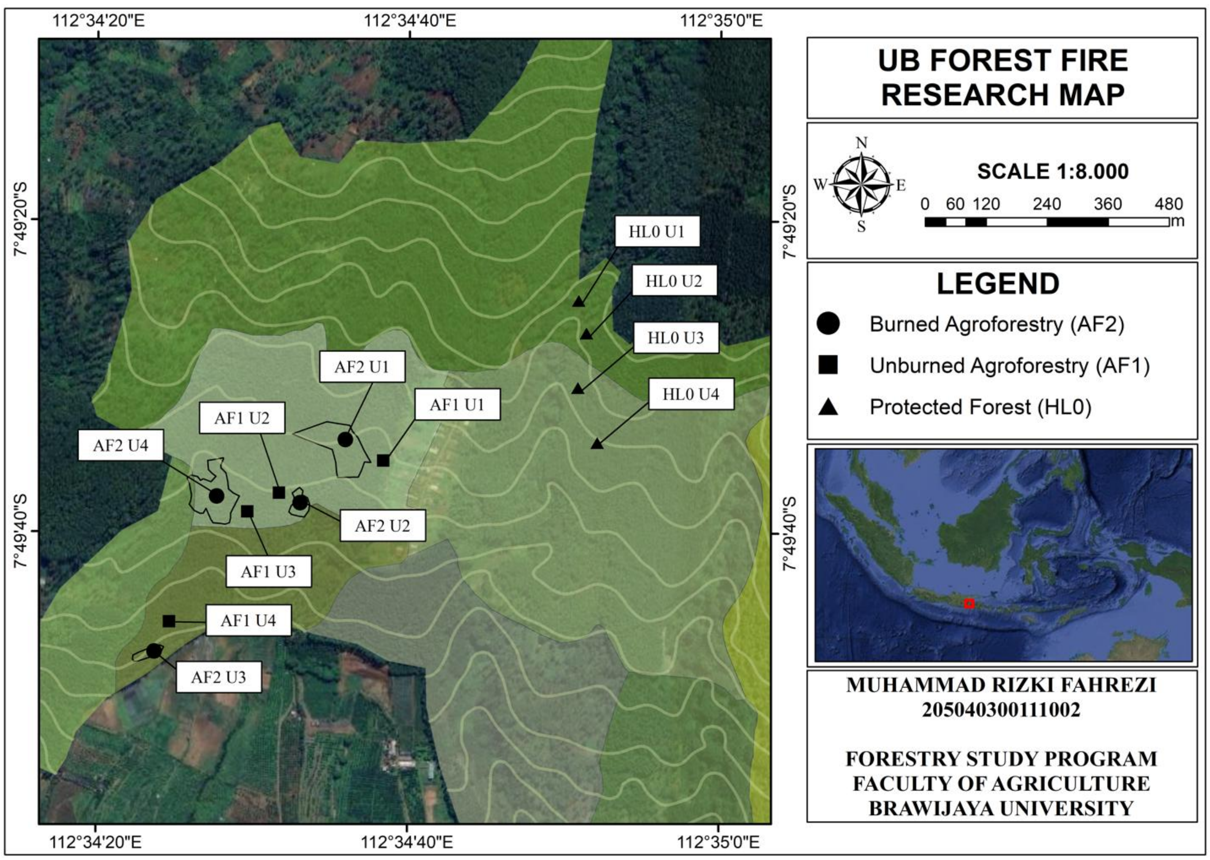


Figure 1. Research location in the UB Forest Area (forest education of Universitas Brawijaya)

### 2.2. Research Design and Data Collection

The research design applied was a factorial randomised block design, which allowed for analysis of the interaction between two treatments factors, namely the first factor being the type of land uses system, consisting of protected forest (HL0), unburned agroforestry (AF1), and burned agroforestry (AF2), while the second factor is soil depth (0-10 cm and 10-30 cm). Each treatment within a factor was replicated 4 times, resulting in 3 land-use systems × 2 soil depths × 4 replicates = 24 samples. The plots used were 20 m x 20 m in size and divided into 5 sub-plots measuring 5 m x 5 m. Soil samples were collected at two depths in each plot, namely 0-10 cm and 10-30 cm (Figure 2). Sampling was conducted purposively based on the representation of vegetation and soil conditions. Data collection was conducted by measuring land characteristics and taking soil samples for analysis. Observed variables include particulate organic matter (POM) content, bulk density (BD), porosity, texture, and soil organic matter, as well as vegetation parameters such as tree density, basal area (BA), canopy cover, and litterfall.

### 2.2.1. Land Characteristics Measurement

Land characteristics were measured by establishing 20 m × 20 m observation plots, each containing five 5 m × 5 m subplots (Figure 2a). Land measurements were taken by measuring tree diameters at a height (DBH) of 1.3 m above the ground, determining canopy cover percentage using the Canopy Apps software, and measuring litter on the ground using a 50 cm × 50 cm frame. Litter sampling was also conducted within the five 5 m × 5 m subplots (Figure 2c).

The data obtained from land characteristics were then analyzed for basal area and percentage of canopy cover. The formula for determining basal area was calculated from tree trunk diameter obtained by measuring the trunk circumference at a height of 1.3 metres above ground level, then converted using the formula $(¼)\pi D^2$.

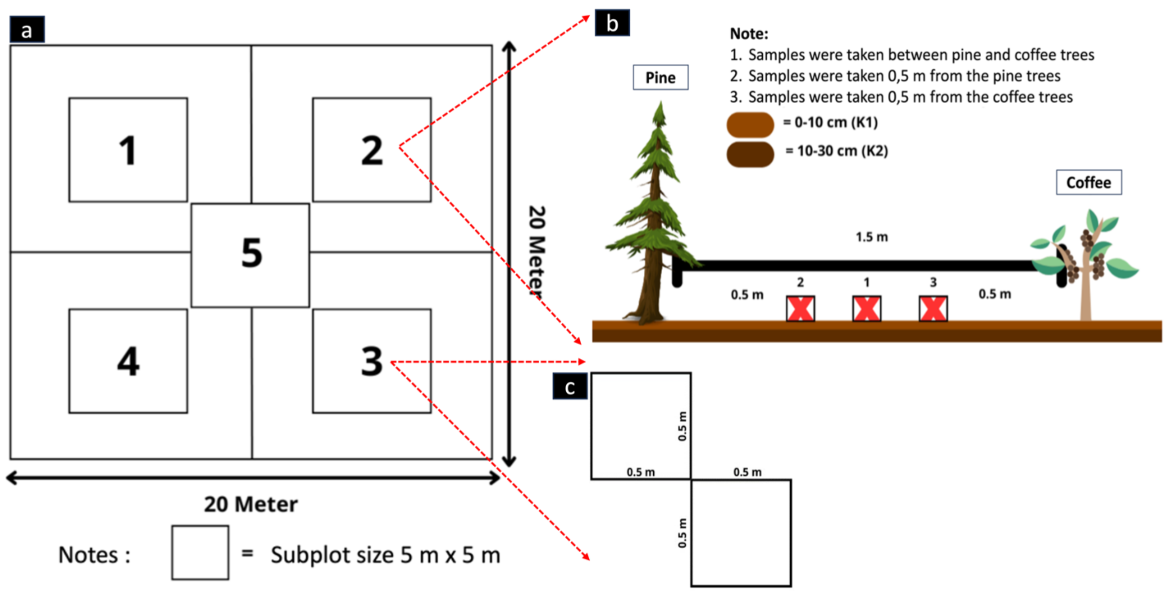


Figure 2. a) Observation plots for tree measurements and canopy cover, b) soil sampling plot, c) observation plots for litter

### 2.2.2. Soil Sampling and Analysis

Soil samples were collected at two depths, namely 0-10 cm and 10-30 cm in each 5 m x 5 m sub-plot (Figure 2). Sampling was conducted using a purposive approach based on vegetation and soil conditions. Undisturbed soil samples were collected from the centre of each plot for analysis of bulk density and porosity, while disturbed soil samples were collected from three different distances from trees (0.5 m from the pine trees, 0.5 m from the coffee trees, and 1.0 m between pine and coffee trees) as composites from each sub-plot (Figure 2b) for analysis of texture, organic matter, and POM. All soil samples were then analyzed at the Soil Chemistry Laboratory and Soil Physics Laboratory, Faculty of Agriculture, Universitas Brawijaya. Laboratory analyses were conducted according to established standards for each parameter.

The measurement of soil parameters, texture was analyzed using the pipette method, bulk density was calculated using the cylinder method, and porosity was determined based on the formula 1 – (BI/BJ). Soil bulk density and porosity was calculated according to Equation (1) and (2), respectively.

$$BD = \frac{W_d}{V_t} \tag{1}$$

$$P = \left(1 - \frac{BD}{PD}\right) \times 100\% \tag{2}$$

where *BD* is soil bulk density (g/cm³ or Mg/m³), $W_d$ is oven-dry soil weight at 105 °C (g), $V_t$ is total volume of soil sample (cm³), and *PD* is particle density. Commonly used *PD* values for mineral soils are *PD* = 2.65 g/cm$^3$

Organic matter content was calculated based on organic carbon content multiplied by a factor of 1.724 using the Walkley and Black method (Walkley & Black, 1934). POM content was analyzed using fractionation techniques based on particle size, namely coarse fraction (>250 µm), medium fraction (53–250 µm), and fine fraction (<53 µm), in accordance with the methods developed by Mikha & Marake (2023) and Leuthold *et al*. (2024).

### 2.3. Statistical Analysis

The data obtained was then processed and tested for normality using Shapiro-Wilk. Normal data was then subjected to ANOVA (Analysis of Variance) testing to determine the significant effect of land use type and soil depth treatments on the dependent variables, particularly POM. If there were significant differences between treatments, the Least Significant Difference (LSD) test was then conducted at a significance level of 5%. Additionally, Pearson's correlation test was applied to determine the relationship between POM and other parameters such as porosity, litter, canopy cover, and bulk density. All statistical analysis processes were conducted using R Studio software version 4.3.3, which supports script-based data processing and enables in-depth visualisation of statistical test results.

## 3. RESULTS AND DISCUSSION

### 3.1. Results

#### 3.1.1. Land Characteristics in various land use systems

Based on the data in Table 1, there are significant differences in vegetation composition, tree density, basal area (BA), canopy cover, and total litter between the three land use systems, namely Protected Forest (HL0), Unburned Agroforestry (AF1), and Burned Agroforestry (AF2). On the other hand, there are also significant differences in soil properties, such as soil bulk density and soil porosity. In general, both the burned and unburned agroforestry LUS have higher tree density, basal area, and bulk density compared to protected forest, while soil porosity is lower in AF2 than in other land use systems.

Table 1. Characteristics of vegetation components in various land use systems

| LUS | Number of species | Tree density (individual ha$^{-1}$) | Basal area (m$^2$ ha$^{-1}$) | Canopy cover (%) | Total litter quantity (Mg ha$^{-1}$) | Bulk density (g cm$^{-3}$) | Porosity (%) | Soil Texture |
|---|---|---|---|---|---|---|---|---|
| HL0 | 13 | 975 b | 17.16 b | 85 a | 5.61 a | 0.64 c | 66.48 a | Silty loam |
| AF1 | 2 | 3850 a | 25.11 a | 77.5 b | 7.74 a | 0.83 b | 62.37 a | Silty loam |
| AF2 | 2 | 4075 a | 26 a | 77.9 b | 5.02 a | 0.95 a | 54.93 b | Silty loam |

Notes: HL0 = Protected Forest, AF1 = Unburned Agroforestry, AF2 = Burned Agroforestry, Different letters indicate significant differences ($p$<0.05)

This study number of species vegetation in protected forest (HL0) was 13 species with the composition consists of various endemic and introduced tree species such as beringin (*Ficus benjamina*), bendo (*Artocarpus elasticus*), cempaka (*Magnolia champaca*), dadap (*Erythrina subumbrans*), kaliandra (*Calliandra calothyrsus*), kina (*Cinchona sp.*), jabon (*Anthocephalus cadamba*), jamuju (*Podocarpus imbricatus*), Nangka (*Artocarpus heterophyllus*), pasang (*Quercus sp.*), pulai (*Alstonia scholaris*), rasamala (*Altingia excelsa*), and suren (*Toona sureni*). This high level of species diversity reflects the relatively natural state of the ecosystem and minimal anthropogenic disturbance

(Sukwika *et al*., 2020). In contrast, both agroforestry systems (AF1 and AF2) are dominated by a combination of pine (*Pinus merkusii*) and coffee (*Coffea arabica*), resulting in a more homogeneous vegetation structure than the protected forest (HL0).

Although HL0 had the lowest tree density of 975 individuals $ha^{-1}$ with a basal area (BA) of 17.16 $m^2$ $ha^{-1}$, this system actually exhibited the highest canopy cover, reaching 85%. In contrast, the agroforestry systems had vegetation densities approximately four times higher of 3,850 individuals $ha^{-1}$ in AF1 and 4,075 individuals $ha^{-1}$ in AF2, accompanied by increases in basal area to 25.11 and 26.00 $m^2$/ha, respectively. However, these increases in density and LBD were not accompanied by an increase in canopy cover, as the canopy cover values for AF1 and AF2 were relatively similar, at only 77.5% and 77.9%, respectively.

Differences in land use systems have a significant impact on the physical characteristics of soil, particularly bulk density and porosity. The Protected Forest (HL0) system exhibited the best soil physical quality compared to the other two agroforestry systems. This was indicated by the lowest bulk density (BI) value of 0.64 g/$cm^3$, followed by the highest porosity of 66.4%. In contrast, the unburned agroforestry system (AF1) exhibits transitional soil physical characteristics, with a bulk density of 0.83 g/$cm^3$ and a porosity of 62.3%, while the post-fire agroforestry system (AF2) shows the highest level of soil physical degradation, with a bulk density of 0.95 g/$cm^3$ and the lowest porosity at 54.9%.

Overall, these results confirm that land use systems influence vegetation structure and its function in terms of canopy cover and litter accumulation. Protected forests show a more stable ecological role with the highest canopy cover values, while agroforestry systems are more productive in terms of litter biomass but less so in terms of canopy protection. The impact of forest fires has also been shown to significantly influence litter input accumulation, even though vegetation regrows quickly.

### 3.1.2. Particulate organic matter (POM) content in various land use systems after the fire

The content of soil organic matter, particularly the Particulate Organic Matter (POM) fraction, is an important indicator in assessing soil quality and fertility, especially in ecosystems that have been disturbed, such as by fire. Based on the result of statistical analysis, the content of soil organic matter fraction (Particulate Organic Matter/POM) in various post-fire land use systems showed significant differences, particularly in coarse POM and total POM fractions ($p<0.05$). However, no significant differences were observed among land use systems for the medium and fine POM fractions. Furthermore, the interaction between various land use systems and soil depth factors also did not show any significant differences (Figure 3).

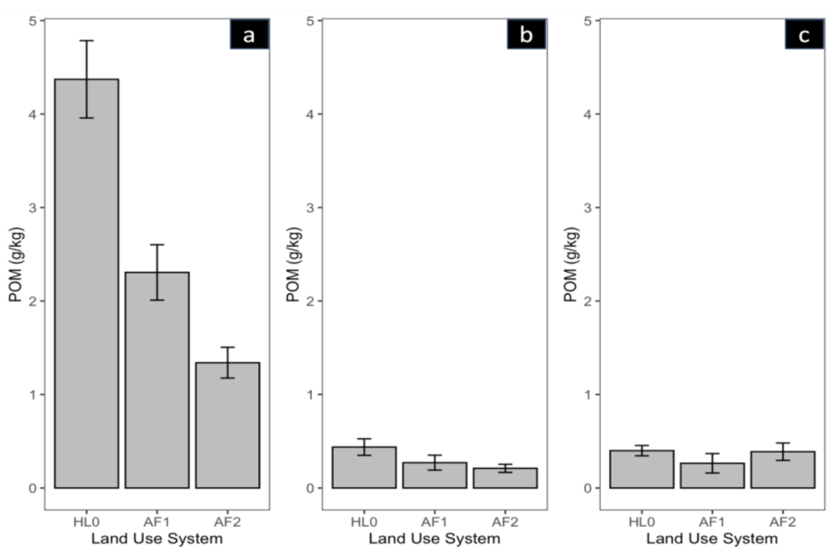


Figure 3. POM content a) coarse, b) medium, c) fine in various land use systems

In general, the burned agroforestry system (AF2) had the lowest total POM content of 1.93 g/kg, representing a decrease of approximately 32% compared to the unburned agroforestry system (AF1) of 2.84 g/kg and 63% compared to the protected forest (HL0) of 5.20 g/kg. A similar trend was observed in the coarse POM fraction, which contributed the largest proportion to total POM across all land use systems. Protected forest (HL0) had the highest coarse POM content with a value of 4.37 g/kg, followed by unburned agroforestry (AF1) with a value of 2.30 g/kg, while burned agroforestry (AF2) had the lowest, around 1.34 g/kg. The decrease in coarse POM in the land use systems of AF2 conditions indicates that its fraction is highly vulnerable to fire disturbance because it consists largely of newly deposited and partially decomposed plant remains, so it is quickly oxidized and destroyed by extreme temperature during fire. Consequently, fire not only reduces direct carbon input to the soil but also limits the availability of substrates for microbial activity and aggregate formation, thus slowing the recovery of soil carbon sequestration processes. The fine and medium POM fractions in the three types of land were relatively low and did not show statistically significant differences, ranging from 0.26 to 0.40 g/kg and 0.21 to 0.44 g/kg, respectively. This indicates that these two fractions tend to be more stable in ecosystem disturbances (such as fire) than coarse POM.

Based on the statistical analysis results in Table 2, there are significant differences in the overall POM fractions (fine, medium, coarse, and total) between depths of 0–10 cm and 10–30 cm in all land use systems ($p<0.05$). This can be seen in the POM content at a depth of 0-10 cm, which shows lower values compared to a depth of 10-30 cm.

Table 2. Total POM content between depths at all land use systems

| Soil Depth (cm) | POM C (g kg$^{-1}$) | | | Total POM | RPOM (% from total POM) | | |
|---|---|---|---|---|---|---|---|
| | Fine | Medium | Coarse | (g kg$^{-1}$) | Fine | Medium | Coarse |
| 0-10 | 0.15 b | 0.17 b | 2.25 b | 2.59 b | 9.14 | 8.22 | 82.64 |
| 10-30 | 0.54 a | 0.43 a | 3.08 a | 4.06 a | 14.23 | 10.22 | 75.55 |

Notes: Different letters indicate significant differences ($p<0.05$)

Overall, total POM at a depth of 0–10 cm was approximately 36% lower than at a depth of 10–30 cm, including across all size fractions (coarse, medium, and fine) (Table 2). This is because at a depth of 0–10 cm, much of the litter and organic material is lost due to burning, resulting in lower POM content. However, this may also be caused by vegetation with deep roots, which leads to the accumulation of organic matter at a depth of 10-30 cm (Ferreira *et al*. 2018). Fires are known to remove most of the easily combustible organic matter, especially coarse POM components, thereby drastically reducing soil organic carbon reserves. This condition can worsen soil quality due to the loss of energy sources for soil microorganisms and the decline in soil aggregate stability.

#### 3.1.3. Relationship of POM fractions and litter production, soil physical properties, and canopy cover

POM dynamics are influenced by various factors such as canopy cover, litter input, and soil physical properties such as porosity, texture, and bulk density. The analysis results indicate that the content of Particulate Organic Matter (POM) in the soil is strongly related to several environmental variables, especially canopy cover, soil porosity, and soil bulk density (Figure 4). The relationship between total POM and canopy cover is positively correlated and quite strong (r = 0.66), indicating that the denser the canopy cover, the higher the POM content in the soil. This condition can be explained by the role of canopy cover in reducing the intensity of run-off, preventing erosion, and maintaining micro-humidity that supports soil microorganism activity and organic matter accumulation. This mechanism contributes to reducing erosion and leaching of organic matter, while creating an environment that supports the activity of soil microorganisms in the process of transforming organic residues into POM (Rabbi *et al*., 2024; Han *et al*., 2024). Furthermore, the strong negative correlation between total POM and soil bulk density (r = -0.68) indicates that an increase in POM content is associated with a decrease in soil density. High POM content allows for the formation of more stable soil aggregates, which directly increases pore space and reduces soil compaction. This is further supported by the positive relationship between POM and soil porosity (r = 0.62), indicating that increased organic matter promotes the formation of a more porous soil structure, thereby improving air and water circulation in the soil.

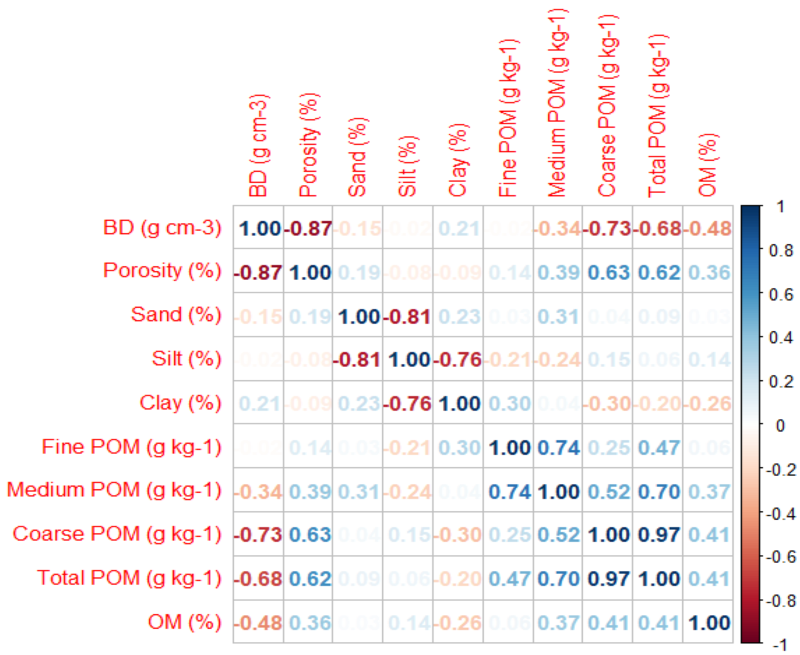


Figure 4. Relationship between POM and physical soil properties in heatmap form

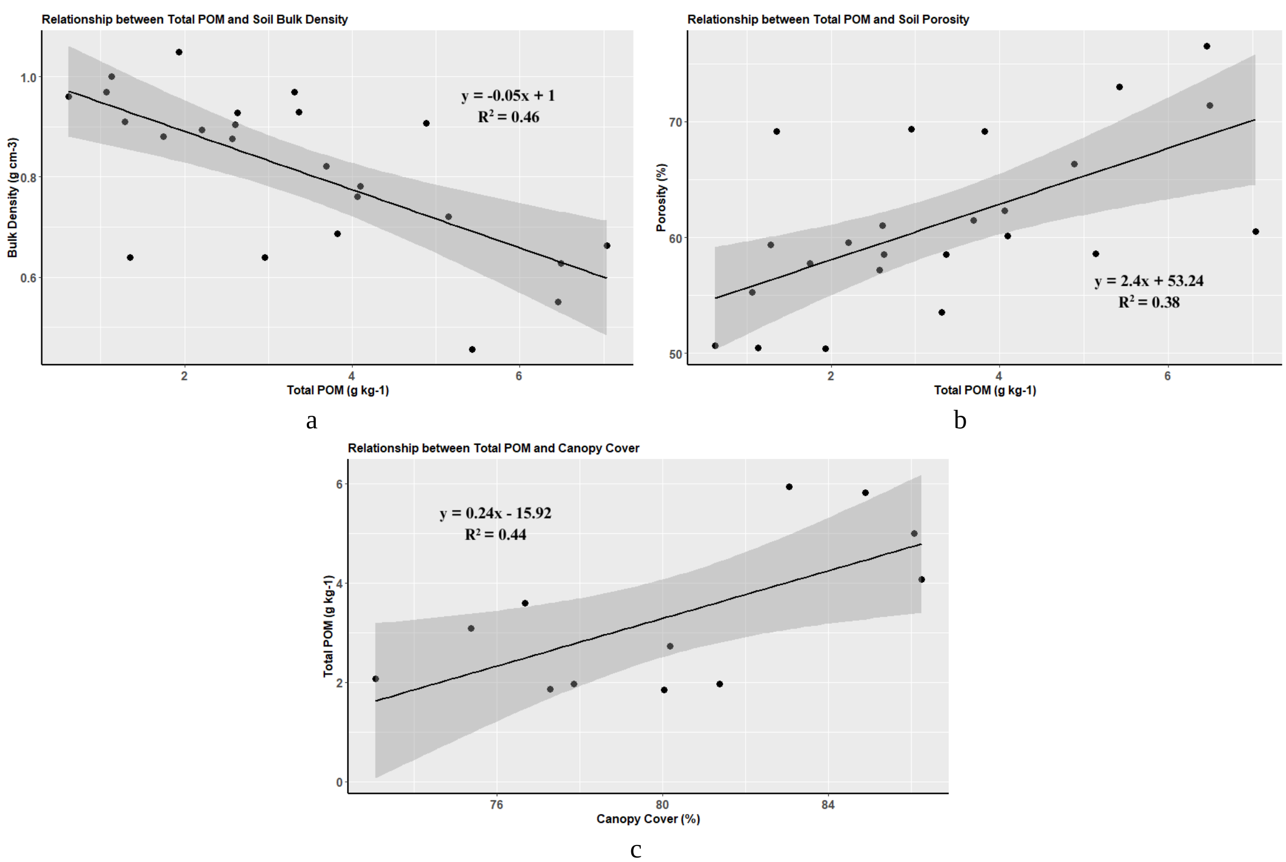


Figure 5. Relationship of: (a) Total POM and soil bulk density, (b) Total POM and soil porosity, and (c) Total POM and canopy cover

Meanwhile, no significant relationship was found between total POM and litter production (r = -0.12), indicating that the quantity of litter fall onto the soil does not directly reflect POM content. This is likely due to variations in litter composition and decomposition rates, as well as the dominant influence of past weathering residues in forming current POM. Similarly, analysis of the relationship between POM and soil texture fractions (particularly clay) showed no significant relationship. Although clay fractions can influence organic matter dynamics through physical protection against decomposition, in the context of this study, texture does not appear to be the primary controlling factor for POM variation. This aligns with previous research findings indicating that the role of texture in organic matter is indirect through soil aggregate formation, rather than through a linear relationship with POM content. Thus, it can be concluded that the presence of POM in soil is more influenced by physical and biological conditions related to vegetation structure and soil quality than by litter input or texture characteristics alone. Thus, these results emphasise the importance of vegetation structure and soil physical quality in maintaining soil organic matter content.

### 3.2. Discussion

Forest fires have been shown to alter the stability and distribution of soil organic matter (SOM) fractions, particularly particulate organic matter (POM), across various land use systems in the UB Forest area. The lowest total POM and coarse POM content in the burned agroforestry system (AF2) compared to the unburned agroforestry system (AF1) and the protected forest (HL0) indicates that fires not only remove the litter layer but also slow the recovery of labile carbon stocks, which play a crucial role in maintaining soil quality. In contrast, protected forests are able to maintain the highest POM content because they receive a continuous input of litter of varying quality, supported by greater vegetation diversity and a more complex canopy structure. These conditions create a more stable environment for organic matter accumulation while protecting the soil from extreme fluctuations in temperature and moisture. These results align with the concept that vegetation complexity plays a key enhancing ecosystem resilience to fire disturbances (Aslan *et al*., 2024; Sari *et al*., 2025).

The greatest decrease in coarse POM in AF2 indicates that this fraction is the SOM component most vulnerable to fire. Most coarse POM originates from relatively fresh and partially decomposed plant residues and represents a comparatively unprotected and labile pool of soil organic matter. Consequently, coarse POM is particularly vulnerable to thermal oxidation and combustion during fire, whereas organic carbon associated with minerals or physically protected within stable aggregates tends to be more resistant to fire-induced losses (Krichels *et al*., 2025; Lipson *et al*., 2026). The loss of these fractions reduces the supply of carbon and energy for soil microorganisms while also decreasing aggregate formation. Consequently, soil structure becomes denser, porosity decreases, and water infiltration declines. This pattern is consistent with the high bulk density and low porosity observed in burned agroforestry systems (AF2), suggesting that the post-fire decline in soil physical quality is more closely related to the loss of labile organic matter than to changes in soil texture.

The distribution of POM at each soil depth also shows that the 0-10 cm depth is the most affected by the fire. This layer was directly exposed to heat and served as the primary siti for litter accumulation, resulting in greater carbon loss. On the other hand, the 10-30 cm depth is relatively protected by the soil matrix, which insulates against heat, and still receives carbon inputs from root biomass, root exudates, and root turnover process. These conditions indicate that soil carbon recovery occurs gradually throughout the soil profile, with the surface layer requiring a longer recovery time compared to the lower layers (Zhou *et al*., 2024).

The strong positive correlation between total POM and canopy cover indicates the important role of vegetation structure in regulating post-fire SOM dynamics. Dense canopy cover contributes to improved microclimatic conditions by reducing soil temperature fluctuations and enhancing moisture retention, which in turn supports the preservation and stabilisation of organic matter (Kokila *et al*, 2024; Lal, 2015). In agroforestry systems, trees with well-developed canopies can partially mitigate the effects of fire by reducing surface heating and limiting post-fire erosion, thereby supporting the retention of labile SOM fractions. These findings are consistent with previous studies indicating that structurally complex agroforestry systems are more resilient to fire disturbances and more capable of supporting soil recovery than simplified systems (Aslan *et al*., 2024; Marques *et al*., 2022). The significant negative relationship between POM and bulk density and the positive relationship with soil porosity confirms the close relationship between SOM fractions and soil physical quality. POM acts as a temporary binding agent in the soil aggregation process through interactions with mineral particles, roots, and soil biota, thereby increasing aggregate stability and pore space development (Even & Cotrufo, 2024). Soils with higher POM contents generally exhibit lower compaction, greater porosity, and better structural resilience, which are critical for post-fire soil recovery. These results are consistent with the findings of Cao *et al*. (2024) and a more recent study by Xuan *et al*. (2022) which showed that the labile SOM fraction plays a key role in mitigating physical degradation in disturbed soils.

These findings have important implications for post-fire land management. The very rapid response of coarse POM to disturbance suggests that this fraction has the potential to serve as a more sensitive indicator than total organic carbon for detecting soil degradation in its early stages. Therefore, the success of restoration should not be assessed solely based on vegetation recovery of soil organic matter dynamics. Techniques and strategies that can accelerate POM accumulation, improve soil structure, and enhance the soil's water-holding capacity include returning litter, applying organic mulch, compost, and biochar, using green manure, and planting cover crops or legumes.

However, the results of this study are still limited to post-fire observations and have not yet evaluated the long-term dynamics of the recovery of soil organic matter fractions or changes in microbial communities and soil enzyme activity that play a role in the formation of POM. Therefore, future research should combine long-term observations with more complete carbon fraction analysis, as well as biological approaches and sensor-based monitoring technologies, to provide a more comprehensive understanding of post-fire soil recovery mechanisms.

Overall, the results of this study indicate that fire not only causes vegetation loss but also alters soil carbon dynamics, degrades soil physical quality, and reduces hydrological functions that support ecosystem sustainability. The sensitivity of coarse POM to fire makes it a promising indicator for monitoring both soil degradation and the success of soil restoration. The integration of vegetation recovery, increased soil organic matter, and precision restoration technologies is expected to accelerate land restoration and enhance the resilience of tropical agroforestry systems to future fires.

The novelty of this study lies in identifying coarse particulate organic matter (coarse POM) as a sensitive indicator of soil degradation following fire disturbance in tropical agroforestry systems. Unlike studies focusing mainly on total soil organic carbon or individual soil properties, this study integrates POM fractions with vegetation structure and soil physical properties across protected forest, unburned agroforestry, and burned agroforestry systems. The strong reduction of coarse POM in burned agroforestry and its relationships with canopy cover, porosity, and bulk density highlight the sensitivity of this carbon pool to disturbance and the potential role of vegetation structure in maintaining soil quality. These findings contribute to the use of coarse POM as an early indicator of post-fire soil condition and provide a practical basis for vegetation-based restoration and sustainable agroforestry management in tropical landscapes.

## 4. CONCLUSION

This study confirms that particulate organic matter (POM), especially its coarse fraction is highly sensitive to land cover changes and fires. Forest degradation and fires significantly reduce total POM, with fires causing a reduction of more than one-third of topsoil organic matter. Positive correlations with canopy cover and soil porosity, as well as negative correlations with bulk density, confirm the role of POM in maintaining loose soil structure. Ultimately, this study emphasizes that the preservation of vegetation cover and the enhancement of soil organic matter are crucial for maintaining POM fractions, which serve as key indicators of post-fire tropical ecosystem recovery.

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## DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE MANUSCRIPT PREPARATION

Not applicable. The authors did not use any generative AI tools or services in the preparation of this manuscript. All content is entirely the intellectual work of the authors.

## AUTHOR CONTRIBUTION

| Author | C | M | So | Va | Fo | I | R | D | O | E | Vi | Su | P | Fu |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MRF | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | | | |
| RMI | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | |
| SK | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | | ✓ | | ✓ |

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|---|---|---|---|
| C: Conceptualization | Fo: Formal Analysis | O: Writing - Original Draft | Fu: Funding Acquisition |
| M: Methodology | I: Investigation | E: Writing - Review & Editing | P: Project Administration |
| So: Software | D: Data Curation | Vi: Visualization | |
| Va: Validation | R: Resources | Su: Supervision | |

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