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The Dynamics of Soil Organic Matter Fractions in Cacao-Based Agroforestry Systems

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ABSTRACT

Soil degradation is an important problem affecting crop production, especially in cocoa agroforestry systems, where soil health is crucial for optimal results. However, the effect of land management on changes in soil organic matter (SOM) content is often not visible through measurements of total soil organic carbon (SOC) content. This study investigates the distribution of soil organic matter fractions across various land-use gradients and soil depths in cacao-based agroforestry landscapes in Southeast Sulawesi, Indonesia. Soil samples were collected from three villages representing different parts of a watershed and subjected to density fractionation to separate light (LF), intermediate (IF), and heavy (HF) fractions. Our results indicate that remnant forests (RF) maintain higher total SOM fractions, followed by cacao-based complex and simple agroforestry (CAF, SAF), particularly in the 0-10 cm soil depth. In contrast, annual crops (CR), exhibit the lowest SOM fractions. Standing litter and decomposition rates significantly influence the LF, while HF shows minimal variation across land-use systems, suggesting long-term stability. The LF also strongly correlates with SOC content, highlighting its responsiveness to recent organic inputs. The findings underscore the importance of diverse litter inputs and tree diversity in enhancing SOM fractions and SOC content in agroforestry systems. The study concludes that complex cacao-based agroforestry systems can effectively mimic natural forest conditions, promoting soil health. These insights provide valuable knowledge for sustainable land management practices to mitigate soil degradation and improve soil quality in cacao production systems.

Keywords: Soil health; light fraction of SOM; soil quality; C organic

INTRODUCTION

Soil degradation poses a significant threat to crop production in agricultural systems, including cacao production systems, where soil fertility plays a crucial role in obtaining optimal yield. Intensive agricultural practices can gradually cause soil quality to decline. The absence of perennial vegetation that can cover the soil increases soil exposure and temperature (Stevens et al., 2015). It reduces the supply of aboveground litter as a source of soil organic matter (SOM). These unfavourable conditions could reduce soil organic carbon (SOC), disrupt plant productivity, and accelerate anthropogenic soil degradation (Lal, 2004; Saputra et al., 2020). Apart from plant and disease, low quality of planting materials, and insufficient post-harvest handling, soil degradation, which is associated with declined soil fertility, become one of the causes behind the declining production of Indonesian cacao (Saputra et al., 2020; Vaast et al., 2016). Under "full-sun" systems, cacao showed better performance in production but is reported to be less ecologically sustainable due to having greater vulnerability to climate extremes and relatively poor soil conditions (Saputra et al., 2024).

On the other hand, cacao-based agroforestry systems have been recognized for their potential to slow down soil degradation (Saputra et al., 2020). Through litter, the cacao-based agroforestry system protected the soil surface because its litter residence time was over a year (Sari et al., 2022). Furthermore, diverse litter inputs from various plant species play an important role in maintaining SOM input, which in turn benefits soil fertility (Hairiah et al., 2006) and maintains physical properties, including stabilizing aggregates (Castellano et al., 2015; Chaplot & Cooper, 2015).

The role of SOM in maintaining soil fertility in forest areas, including agricultural systems, is well recognized (Lal, 2009) through its soil organic carbon

(SOC) content. SOC is a standard variable used as an indicator to measure soil quality and health to date (De Laurentiis et al., 2024). However, low variations in SOC content often yield insignificant results across different land-use management practices (Lal, 2004). It is probably due to the close relationship between carbon (C) organic with clay content and soil pH. To eliminate that effect, van Noordwijk et al. (1997) suggested making corrections by calculating carbon reference (Cref) by considering clay content, dust, pH, and soil depth into the equation, aiming to obtain the optimal comparable value of SOC.

In some cases, these adjustments were inadequate to explain the effects of land management on soil fertility status. A recent study conducted by Saputra et al. (2020) in the cacao production system in Konawe district, Southeast Sulawesi, reported that there was no difference in SOC, including corrected SOC (Corg/Cref), across the land-use gradient, which represents different land management. It indicates that land management did not affect SOM. It also could interpret that implementing agroforestry practices and monoculture systems did not change SOM, leading to the mislead conclusions. However, Sheng et al. (2015) and Tan et al. (2007) mentioned that changes in SOC with changes in land use management can partly be explained by how C is allocated to different SOM fractions.

SOM contains fractions exhibiting different turnover rates and interactions (Ludwig et al., 2015; Sollins et al., 1996). The dynamics of soil organic carbon (SOC) are commonly studied by categorising soil organic matter (SOM) into distinct physical fractions that management practices can influence (Whalen et al., 2000). Additionally, the link between SOM and the distribution of soil aggregates of different sizes is often used to characterise SOC dynamics (Ontl et al., 2015; Schmidt et al., 2011). The fractions of SOM are physically separated using laboratory processes by density fractionation, which divides the soil into light (LF), medium (IF), and heavy (HF) fractions (Six et al., 2002). This method is valuable for evaluating labile SOM pools and is more responsive to cropping techniques than total SOC pools in temperate soils (Bremer et al., 1994; Janzen et al., 1992). LF is a term used to describe a proportion of organic matter that is similar to plants and is less stable but has a high concentration of carbon (Gregorich et al., 1996). The significance of light fractions, which encompass both free and occluded organic carbon within aggregates, is well-established due to their contribution to the development and durability of soil structure, particularly in the stabilisation of soil macro aggregates larger than 250 mm (Kay et al., 1998).

In contrast, HF is a more stable organomineral fraction, contains more processed SOM, has a high density which has a lower C concentration, is stored in soil aggregates, and serve as the primary sink for soil C storage due to its low mineralizable carbon content (Chaplot & Cooper, 2015; Ontl et al., 2015). SOM in cultivated agricultural soils may consist of 1±25% of LF organic matter (Janzen et al., 1992), whereas SOM in forest soils may contain as much as 63% LF organic matter (Boone, 1994). There is limited available data, however, that quantifies these fractions and examines their impact on the overall storage of SOC due to changes in land use practices (Tan et al., 2007), especially at SOM fractions in various soil depths. In addition, factors influencing the presence of LF, IF, and HF, such as litter input (quantity and quality), litter decomposition rate, and aboveground structural composition of the system (tree diversity), are still poorly understood. Ultimately, there is still a research gap in understanding the influence of land management on SOM status in cocoa production systems because previous research did not find clear patterns of SOC content (Saputra et al., 2020).

This study addresses this gap by investigating the variation of SOM fractions across different land-use gradients in a cacao-based agroforestry landscape. Our research questions were 1) Does the variation of soil organic matter fraction (LF, IF, HF) differ across land-use gradient and soil depths? 2) How do standing litter, litter thickness, diversity index, and decomposition rate influence different types of SOM fractions? 3) Does total soil organic matter fractionation positively relate to its soil organic C across the land-use gradient? The results of this study will offer significant knowledge to expand comprehension of the significance of agroforestry systems in sustaining land management techniques (Whalen et al., 2000) and their ability to promote soil health by conserving SOM.

MATERIAL AND METHODS

Description of study site

The study was carried out in the Konawe District, located in Southeast Sulawesi, Indonesia as a follow up study of Saputra et al. (2020); Sari et al. (2020); Sari et al. (2022). The geographical coordinates of the study site range from 3°15’0" to 5°13’0" S and from 121°22'30" to 122°31’0" E. The annual rainfall of the study site ranges from 1500 to 1900 mm, with the daily temperature fluctuating

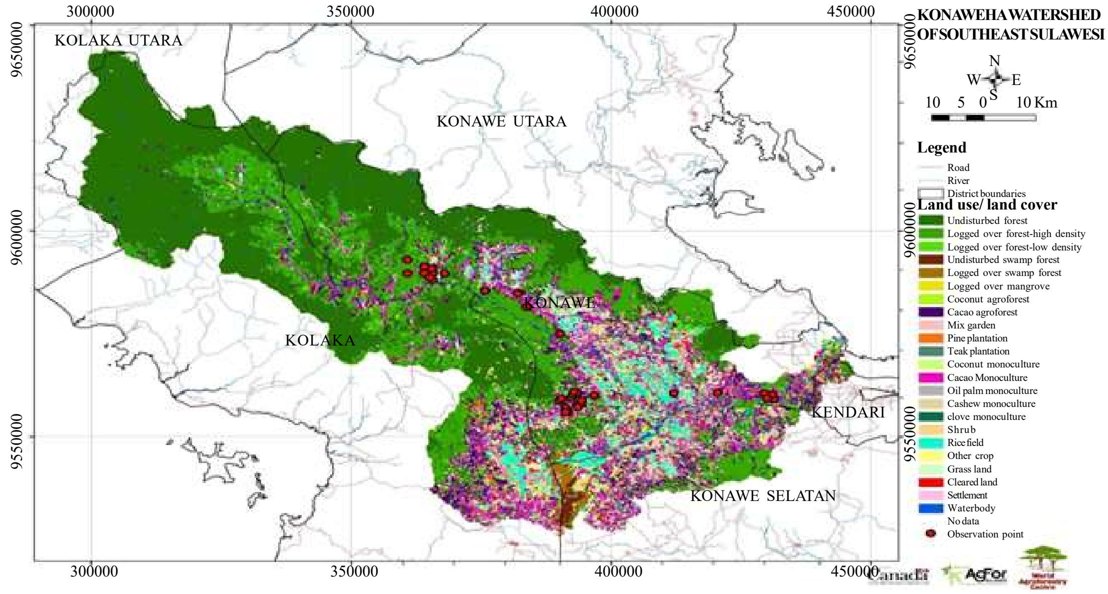

Figure 1. Land cover map of Konaweha Regency, Southeast Sulawesi, Indonesia (World-Agroforestry-Centre, 2014).

between 24 and 31 °C. For a more comprehensive overview of the research area, please refer to Sari et al. (2020). We selected three villages (i.e. Asinua Jaya, Wonuahoa, and Lawonua) to represent the upper, middle, and lower part of watershed (Figure 1). Those three study sites were chosen due to 1) the representation of land-use gradient, and 2) different geographical and characteristics of the watershed (Saputra et al., 2020).

The study sites are the centres of cacao producers in Indonesia. Cacao production systems can be found in most landscapes in both monoculture and mixed (agroforestry) systems. In a complex system, cacao is cultivated alongside various fruit trees (jackfruit, durian, etc.), timber (teak and jabon), and legume trees (*Gliricidia sepium*). Cacao is combined with *Gliricidia sepium* as a shade tree in a simpler system. Remnant forests in this study site are categorized as degraded forests because forest trees were excessively harvested for fuelwood and timber (Saputra et al., 2020). The land-use gradient selected in this study consists of 1) remnant forest (RF), 2) cacao-based complex agroforestry (CAF), cacao-based simple agroforestry (SAF), cacao monoculture (M), and annual crops (CR). Fifteen permanent plots were

Table 1. The characterizations of study site across land-use gradient (RF=remnant forest, CAF=complex agroforestry, SAF=simple agroforestry, M=cacao monoculture, CR=annual crop)

LUS	Tree diversity (H)	Litter quantity (Mg ha^{-1})	Litter thickness (cm)	Litter decomposition rate (k, week^{-1})	MWD of aggregate (mm)	Soil texture
Remnant forest	2.36	6.98	0.39	0.007	2.7	Silty clay – silty clay loam
Complex AF	0.93	7.02	0.47	0.01	2.3	Silty clay – silty clay loam
Simple AF	0.58	5.51	0.28	0.023	0.8	Silty clay – silty clay loam
Cacao monoculture	0.24	4.26	0.24	0.016	1.45	Silty clay – silty clay loam
Annual crop	-	-	-	-	1.6	Silt loam
Data source	Sari et al. (2020)	Sari et al. (2020)	Saputra et al. (2020)	Sari et al. (2022)	Saputra et al. (2020)	Saputra et al. (2020)

constructed across a land-use gradient of 20 m x 20 m. We selected our permanent plots based on several criteria as follows: 1) the age of the cacao plant (minimum of 9 years), 2) a slope ranging from 0 to 15%, and 3) comparable soil texture: silty clay to silty clay loam (Table 1). The detailed plot characterization is presented in Table 1. This study categorized tree diversity in cacao-based agroforestry as having a low to medium Shannon-Wiener index, with a higher index observed in remnant forest (Sari et al., 2020). However, the standing litter and litter thickness in complex agroforestry systems were higher than those in remnant forest (Table 1).

Soil sampling and preparation

At the same point beneath the litter frame of 0.5 m × 0.5 m (Sari et al., 2020), we collected ten soil samples in each 20 m × 20 m permanent plot at three different soil depths (0–10 cm, 10–20 cm, and 20–30 cm). We analysed a composite of fresh soil samples from each soil depth per plot, separating them into light, intermediate, and heavy categories based on density. We also use the same soil sample to determine soil organic C. We determined the soil C content using the Walkey and Black method (Walkley & Black, 1934).

Fractionation of soil organic matter (SOM)

We utilized the density fractionation of micro organic matter procedure using Ludox suspension/colloidal silica suspensions (Meijboom et al., 1995). Firstly, we dry sieved the soil sample through a 2 mm mesh to eliminate roots and coarse litter particles. Secondly, a 1000-gram soil sample was re-wet and allowed to stand for 24 hours. Next, we washed the soil samples on a 150-m sieve with a gentle stream of water and placed a 250-m sieve on top to prevent clogging. Fine aggregates were broken down on the coarser sieve during washing, and the silt and clay particles passing through the 150 ìm sieve were discarded. The stuff that stuck to both sieves was gathered. Large pieces of mineral sand were separated from parts with organic matter by "decantation" in swirling water. The mineral part was then thrown away. The remaining sand-sized fractions were divided into three sub-fractions by sequential immersion in Ludox silica suspensions of densities of 1.13 g.cm^{-3} and 1.3 g.cm^{-3}. A suspension of 1.3 g.cm^{-3} is preferred due to potential viscosity issues (Hairiah et al., 1995). The three resulting fractions were classified as 1) light (LF) because the fraction floated on 1.13 g cm^{-3}, 2) intermediate (MF), the fraction floated on 1.3 g cm^{-3} but not on 1.13 g cm^{-3} suspension), and 3) heavy (HF), the fraction did not float on either. We scooped off the surface material from each suspension, collected the fraction, rinsed it, and dried it in the oven at about 60 °C until a constant weight was achieved, after which we measured its dry weight (g kg^{-1} soil).

Statistical analysis

A two-way ANOVA was performed to assess the physical variation of soil organic matter fraction across the land-use gradient and soil depths. Post-hoc analysis of Tukey's HSD (honestly significant difference) was tested to determine the difference. The level of statistical significance was determined at $\alpha = 0.05$. We applied a multiple regression model to assess the relative importance of standing litter, litter thickness, diversity index, and its decomposition rate on different types of soil organic matter (SOM) fractions. In order to compare effect sizes, we applied a standardisation process to all explanatory variables by subtracting the mean and dividing by the standard deviation (Gelman & Hill, 2006). We performed stepwise regression routines using a linear model ("lm" function from the stats package in R) to explore the relation between soil organic matter fractionation and soil organic C. The statistical analyses used R 4.3.0 (R-Core-Team, 2022).

RESULTS AND DISCUSSION

The distribution of soil organic matter fractions across the land-use gradient

We found that the total fractions of SOM differed significantly ($P<0.05$) across various sizes, soil depths, and land-use systems (Table 2). Generally, remnant forests maintained higher total SOM fractions than agricultural systems, with intensive practices like CR showing the lowest total SOM fractions. The interaction between soil depths and land-use systems was included in the analysis as it improves the model fit. The amount of LF of SOM in RF reached 67% of the total SOM fractions, particularly at 0-10 soil depths. It was approximately twice as high as in the cacao production system (CAF, SAF, and M). This result agrees with Boone (1994) when investigating the contribution of the LF fraction of SOM on net nitrogen mineralization. In cacao-based agroforestry and monoculture, a high proportion of LF was similar to RF but with a lower percentage for about 48, 54, and 61% at 0-10 cm soil depths for M, SAF, and CAF, respectively. We found that the mean of LF SOM in CAF was close to RF, indicating that SOM in agroforestry can imitate the soil condition in the forest soil similar to

Table 2. Overview of the best model for various observed variables.

Observed variable	Statistical method	Best model
a) Total SOM fraction	Linear model	LUS*, size*, depth*, LUS x depth*
Fraction based on its size and density:		
b) Light fraction	Linear model	LUS, depth, LUS x depth*
c) Intermediate fraction	Linear model	LUS, depth, LUS x depth*
d) Heavy fraction	Linear model	LUS, depth, LUS x depth

the result which was reported by Santos et al. (2024) in Brazil where the successional agroforestry became a good alternative to increase SOC as similar as natural systems dominated by Cerrado vegetation. It implies the importance of managing cacao under complex systems as it potentially improves SOC, mimicking RF conditions. It ensures the sustainability of organic matter input for the future. The study by Saputra et al. (2020) could not provide clear proof of the effect of land-use management on soil quality status when relying solely on the measurement of total organic carbon content as the indicator.

Suppose contributed around 19-30% of the total SOM, while HF contributed no more than 3-20% (Table 3). This observed trend was mainly consistent throughout the land-use systems, with a gradual decrease noticed as the soil depth increased (Figure 2), in line with Santos et al. (2024). It could be due to 1) the significant decrease of fresh organic inputs as soil depths increase (Gross & Harrison, 2019); 2) the decline of microbial activity due to lower oxygen levels and reduced availability of organic substrates (Rumpel & Kögel-Knabner, 2011); 3) slower decomposition rates in deeper layer due to limited fresh litter input, microbial activity, and aeration (Naylor et al., 2022). HF of SOM was not significantly different across land-use and soil depths (Table 2d). It suggests that the amount of SOM contributed in the past was consistent and negligible across land-use systems. Given that HF is a more stable fraction that consists of a higher proportion of processed SOM (Whalen et al., 2000), it may be inferred that this SOM originated from the previous land-use system.

Assessing soil fertility requires knowledge of soil organic matter (SOM) fractions because each

Table 3. Proportion (%) of soil organic matter (SOM) based on its physical size and density fractionation (mean ± standard error).

Land-use system	Soil depth	Light fraction	Intermediate fraction	Heavy fraction
		------------------ % -------------------		
Remnant forest (RF)	0-10 cm	67.17±3.31	27.05±2.73	5.77±0.58
	10-20 cm	77.45±1.81	19.88±2.61	2.65±0.80
	20-30 cm	59.77±0.00	31.79±0.00	8.42±0.00
Complex agroforestry (CAF)	0-10 cm	61.38±0.23	28.29±0.18	10.31±0.04
	10-20 cm	63.02±0.11	26.99±0.09	9.98±0.02
	20-30 cm	56.71±0.05	32.32±0.03	10.96±0.08
Simple agroforestry (SAF)	0-10 cm	54.11±0.39	33.92±0.14	11.96±0.24
	10-20 cm	54.30±0.00	34.16±0.00	11.53±0.00
	20-30 cm	46.47±0.97	33.05±0.20	20.47±1.18
Cacao monoculture (M)	0-10 cm	47.75±1.14	37.55±1.22	14.68±0.07
	10-20 cm	46.53±0.25	35.91±0.16	17.55±0.08
	20-30 cm	34.15±0.00	52.26±0.00	13.57±0.00
Crop system (CR)	0-10 cm	51.81±1.74	34.00±1.92	14.17±0.18
	10-20 cm	51.28±2.06	35.80±2.69	12.90±0.68
	20-30 cm	53.83±0.85	30.85±1.09	15.30±0.23

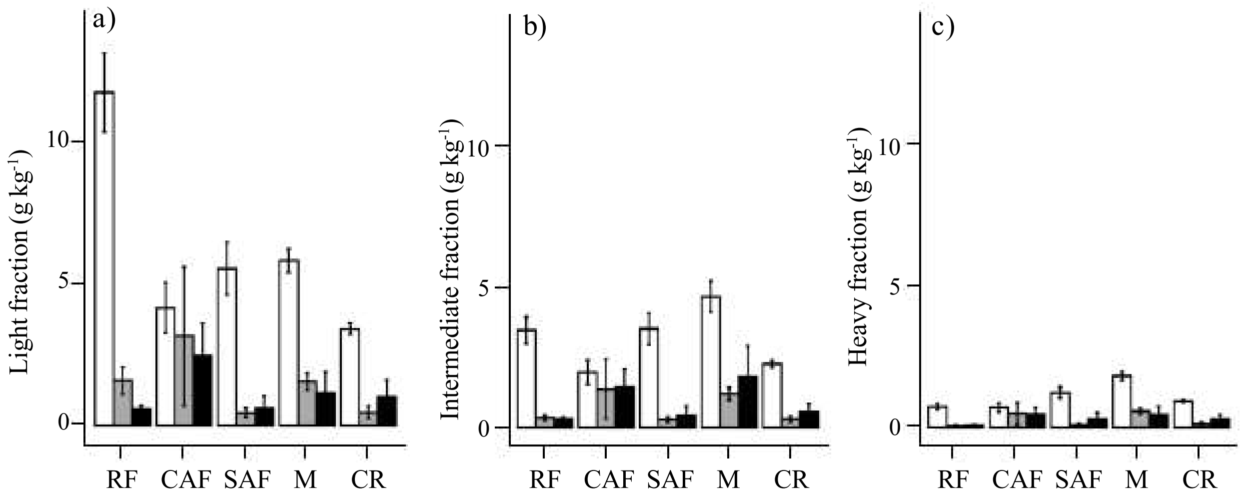

Figure 2. The distribution of soil organic matter (SOM) fraction: a) light, b) intermediate, and c) heavy fraction across land-use gradient and soil depths. □ : 0-10 cm, ■ : 10-20 cm, ■ : 20-30 cm.

component differs in stability, nutrient release potential, and susceptibility to land-use change. LF, often constituted of fresh plant residues, is highly labile and strongly connected to short-term nutrient cycling and microbial activity. Therefore, it is an appropriate indication of recent organic inputs and biological soil health (Poeplau et al., 2018). However, HF is made of mineral-associated organic matter that breaks down gradually and supports long-term carbon storage and soil structure (Lavallee et al., 2020). Especially under different land-use and management systems, the distribution of these fractions offers a more complex knowledge of SOM dynamics than total SOC alone. Litter quantity and quality, decomposition rate, soil texture, plant species variety, and land-use intensity affect the variation in SOM fraction distribution (Lehmann & Kleber, 2015). Therefore, understanding SOM fractionation is vital for designing sustainable land management strategies that maintain or improve soil fertility.

Standing litter and decomposition rate affect a light fraction of SOM

The influence of standing litter, litter thickness, diversity index, and decomposition rate on different soil organic matter (SOM) fractions is multifaceted and critical for understanding soil health and fertility. Using multiple linear regression, we assessed the relative importance of litter input (standing litter), litter thickness, decomposition rate, and tree diversity on each SOM fraction (LF, IF, and HF). We found different patterns of relation among different fractions. Across the land-use gradient, the LF of SOM was strongly driven by a significant, positive effect of standing litter (Figure 3) and an adverse effect of decomposition rate. Litter thickness and tree diversity (H index) did not significantly affect LF. A positive linear relationship between standing litter and LF (Figure 3b), indicating that higher amounts of standing litter were associated with increased LF. High quantities of standing litter typically increase the LF of SOM due to the fresh organic material it provides (Lorenz & Lal, 2005). Furthermore, a negative relationship between decomposition rate (k) and LF (Figure 3c) suggests that higher decomposition rates were associated with lower LF, in contrast with Sollins et al. (1996), who reported otherwise. Tree diversity significantly influenced HF (Figure 4a, b) while no clear pattern was found for IF. Diverse plant communities may enhance the formation of more stable SOM fractions. The presence of multiple plant species can improve soil structure as indicated by the mean weight diameter (MWD) of aggregate (Figure 4c) through the role of increasing root biomass and root diversity (Saputra et al., 2020). Root diversity from various plant species improves soil aggregation, stabilizing SOM by protecting it within soil aggregates (Chaplot & Cooper, 2015; Chevallier, 2011; Ontl et al., 2015).

A positive relation of SOM fractions (light, intermediate, and heavy) and soil organic carbon

Various degrees of relation were noticed between three different fractions of soil organic

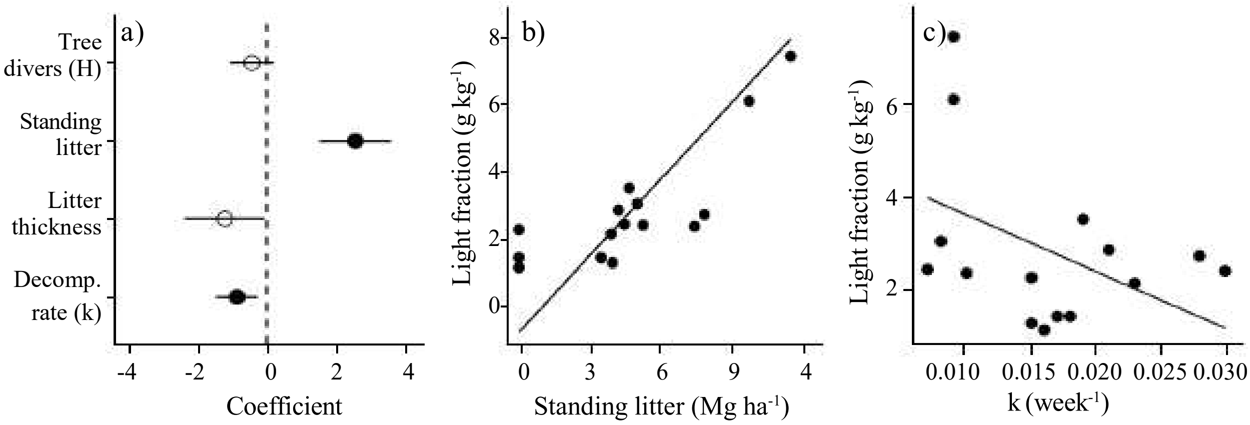

Figure 3. a) The effect of litter variables on soil organic matter's light fraction (LF). The standardised coefficients for all explanatory variables and their corresponding 95% confidence ranges are provided. A coefficient with a negative value signifies a negative correlation, whereas a coefficient with a positive value signifies a positive correlation. Filled symbols denote a substantial response, whereas open symbols indicate an insignificant response. The relationship between the light fraction of soil organic matter with b) standing litter, and c) the decomposition rate (the other explanatory variables were kept constant at the mean).

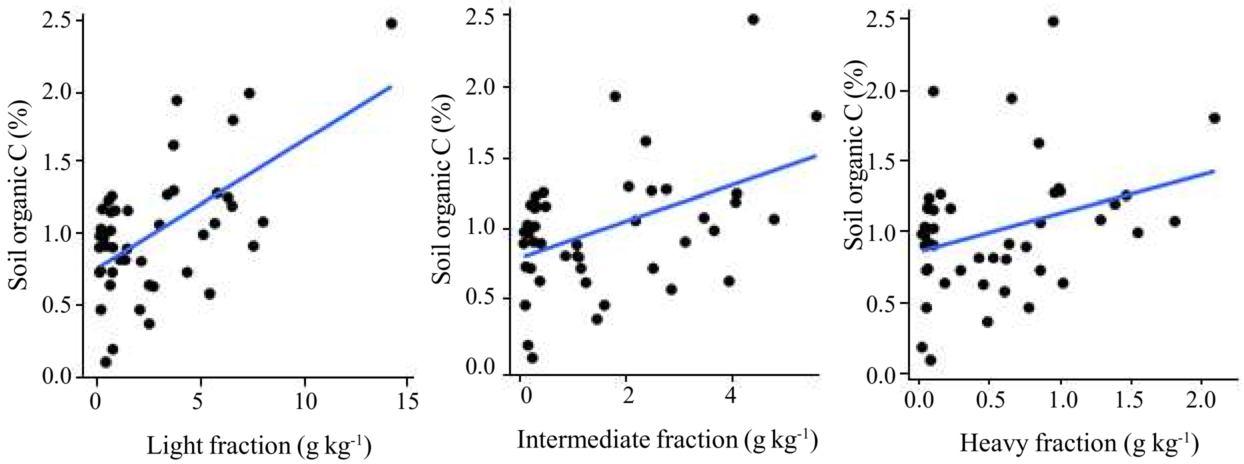

Figure 5. The relationship between three soil organic matter fractions: a) light, b) intermediate, and c) heavy, and soil organic carbon (SOC).

matter (LF, IF, and HF) and soil organic carbon (SOC). A clear association was noted between the light organic fraction and SOC (Figure 5a), indicating that higher levels of the light fraction are positively related to an increase in SOC. This result aligns with Janzen, who found a positive, consistent correlation between LF and SOC in three agricultural soils in Canada. A similar trend was noted in the relationship between IF and HF of SOM with SOC content. However, the association was less pronounced than the light fraction (see Figure 5b, c), particularly for HF.

The correlation between soil organic carbon (SOC) content and HF tends to be lower compared to LF is due to the stabilized, mineral-associated nature of the HF, which is typically older, more decomposed, and chemically complex, making it less responsive to changes in SOC content (Lützow et al., 2006; Six et al., 2002). Slower turnover rate of HF (Sitompul et al., 2000) and its reduced accessibility to microbial activity (Fontaine et al., 2007) mean that changes in SOC content might not be immediately reflected in the heavy fraction. In contrast, the LF is more labile and responsive to recent organic inputs. Barrios et al. (1996) and Luxi et al. (2024) pointed out that LF is also strongly associated with the rate of N mineralization and soil respiration, resulting in increased decomposition rate and greater sensitivity to changes in management practices (Janzen et al., 1992). The LF content serves as a sensitive indication of the impact of cropping on SOM content and composition. However, because of its transient nature, it mainly represents short-term impacts. Sitompul et al. (2000) noted significant fluctuations in low-frequency content, even within a year. These changes are likely caused by several variables, such as the time and quantity of litter input, the amount and type of litter applied, soil moisture, and soil temperature.

CONCLUSION

This research reveals the significant influence of land management on soil organic matter content, especially in terms of fraction distribution. The remaining forests have a higher fraction of total SOM, especially LF, followed by cocoa-based agroforestry and monoculture. A high LF fraction in CAF, close to RF, indicates that SOM in agroforestry can imitate forest soil conditions. It implies the importance of managing cocoa in complex systems because it potentially increases SOC. Additionally, we found that LF was strongly correlated with standing litter, while HF remained stable across land uses, indicating that it persists in the long term. It emphasizes the role of diverse litter inputs and tree diversity in maintaining soil health. It highlights the superior ability of complex agroforestry systems to mimic natural forest conditions, thereby increasing SOC content.

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