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Dynamics of Soil Organic Carbon at Different Elevations in Cocoa Land-Use Systems

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Abstract: Soil organic carbon (SOC) is essential for sustaining soil quality, especially in sloped agricultural landscapes prone to erosion and degradation. This study aimed to analyze SOC dynamics across different elevations (400, 600, and 800 meters above sea level) in cocoa-based land-use systems and examine its relationships with some key physical properties. Soil sampling was conducted using a stratified random design, and laboratory analyses were carried out using standard methods. The results showed that SOC increased with elevation due to cooler temperatures, slower organic matter decomposition, and higher surface litter accumulation. Polynomial regression revealed non-linear relationships between SOC and soil properties, with significant coefficients of determination: SOC vs. bulk density (R^2 = 0.82), SOC vs. penetration resistance (R^2 = 0.44), and SOC vs. saturated hydraulic conductivity (R^2 = 0.37). Moderate SOC levels (around 2.3% – 3.0%) were associated with improved soil structure, lower bulk density, higher hydraulic conductivity, and reduced penetration resistance. However, excessive organic inputs beyond the optimum may reduce these benefits due to incomplete decomposition. A similar curvilinear pattern was found between surface litter and SOC content. These findings highlight the importance of optimizing organic matter management in cocoa systems on sloped lands to enhance soil physical conditions and promote sustainable agriculture.

Keywords: Bulk density; Cocoa land use; Penetration resistance; Soil organic carbon; Surface litter; Elevation.

Introduction

The availability of organic carbon is a key component in maintaining soil health. As a major constituent of soil organic matter, organic carbon plays a crucial role in nutrient retention, improving soil structure, enhancing water-holding capacity, and reducing resistance to root penetration. In addition, soil organic carbon also contributes to mitigating global climate change through carbon sequestration in the soil (Bouajila & Sanaa, 2011; Toková et al., 2020).

The accumulation and stability of soil organic carbon are influenced by various environmental factors, such as climate, vegetative ground cover, litter input, and land management practices. These factors vary considerably depending on elevation (Li et al., 2012). Several studies have shown that soils at higher elevations tend to contain greater amounts of organic carbon due to lower temperatures and slower decomposition rates of organic matter (Adiyah et al., 2022). However, this relationship is not always linear or consistent, as factors such as land-use intensity, soil

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texture, and the quality and quantity of organic matter inputs also play significant roles in determining the accumulation of soil organic carbon (Dawson & Smith, 2007; Navarro-Pedreño et al., 2021).

In agricultural systems that are typically semi-intensive and located on sloped lands, the accumulation of surface litter and minimal mechanical disturbance are factors that contribute to increased soil organic carbon levels. In practice, the conversion of forest land to agricultural use has been shown to significantly reduce soil organic carbon (Don et al., 2011). However, the interactions between organic carbon content and soil physical properties—such as bulk density, saturated hydraulic conductivity, and penetration resistance—across different elevations remain insufficiently explored, particularly in the context of carbon conservation on degraded lands (Tsozué et al., 2019).

This research aimed to analyze SOC dynamics across different elevations (400, 600, and 800 meters above sea level) in cocoa-based land-use systems and examine its relationships with key physical properties, including bulk density, penetration resistance, saturated hydraulic conductivity, soil texture, and surface litter. The findings of this study are expected to provide scientific insights for the management of organic matter and soil quality in sustainable agricultural systems on sloped landscapes.

Method

This research was conducted in Palolo Subdistrict, Sigi Regency, Central Sulawesi, Indonesia. Fieldwork was carried out from January to June 2025, and laboratory analyses were performed at the Soil Science Laboratory, Faculty of Agriculture, Tadulako University, Palu. The study area was selected to represent cocoa-based agroecosystems across different elevations.

Soil sampling was conducted using a stratified random approach based on elevation differences, specifically at 400, 600, and 800 meters above sea level (masl). At each elevation level, both disturbed and undisturbed soil samples were randomly collected from three designated observation points, with three replications conducted at each point. Field equipment included sample rings, GPS devices, wooden blocks, hammers, knives/cutters, plastic sample bags, markers, rubber bands, cameras, labeling paper, and standard field data recording tools. The materials collected included undisturbed soil samples, disturbed soil samples, and surface litter from cocoa plantations at each elevation level. In addition, distilled water and analytical-grade chemical reagents were used to support laboratory analyses.

The observed variables included selected physical and chemical properties of the soil. Organic carbon content was analyzed using the Walkley and Black method. Soil texture was determined by the pipette (hydrometer) method. Bulk density was measured using undisturbed soil cores in stainless steel rings. Saturated hydraulic conductivity was measured using the constant head permeameter method. Soil penetration resistance was measured using a laboratory-modified cone penetrometer. Surface litter dry weight was estimated using a square-grid quadrat method.

Data were analyzed using polynomial regression techniques to describe the non-linear relationships between soil organic carbon (SOC) and other physical soil properties. The regression results were evaluated based on the coefficient of determination (R^2), and additional statistical parameters including the F-statistic, p-value, and standard error of the regression coefficients were calculated to assess the significance and reliability of the models.

Result and Discussion

Soil samples collected at 400 meters above sea level (masl) exhibited a relatively balanced texture among sand, silt, and clay fractions, with organic carbon content ranging from 1.71% to 2.21%. At 600 masl, the sand fraction was dominant (>69%).

The analysis revealed substantial variations in soil physical properties and organic matter content across elevation levels. Soils at 600 meters above sea level (masl) exhibited the highest soil organic carbon (SOC) content (up to 3.18%) and the lowest bulk density (1.06 g/cm^3), indicating favorable structural conditions. In contrast, soils at 400 and 800 masl showed slightly lower SOC content and higher bulk density. Saturated hydraulic conductivity tended to increase in soils with coarser texture and higher organic matter, while penetration resistance demonstrated complex interactions with both SOC and bulk density.

Bulk density exhibited a quadratic relationship with SOC. Initially, increasing SOC reduced bulk density, supporting the role of organic matter in improving soil aggregation and porosity. However, beyond a threshold of approximately 2.2–2.3% SOC, further additions of organic inputs slightly increased bulk density, possibly due to the accumulation of partially decomposed organic materials that clogged micropores. These results indicate the existence of an optimal SOC range that promotes a friable and stable soil structure. These variations serve as the basis for analyzing the relationships among elevation, soil physical properties, and organic matter management in cocoa-based farming systems on sloped land (Table 1).

Penetration resistance was also influenced by SOC in a nonlinear manner. Moderate levels of SOC increased resistance due to enhanced aggregate cohesion, with a peak value of around 2,228 kPa at 2.27% SOC. Beyond this point, increasing SOC led to a reduction in penetration resistance, likely due to improved porosity and loosened soil structure. A similar quadratic trend was observed between bulk density and penetration resistance, with the highest resistance (3,011.57 kPa) at a bulk density of 1.99 g/cm³. These findings suggest that while organic inputs can strengthen soil structure, excessive levels may reduce mechanical strength.

The interaction between bulk density and saturated hydraulic conductivity (Ksat) further supported these trends. Decreasing bulk density correlated with increased Ksat up to an optimal point, reflecting better pore connectivity and water movement. However, excessively low bulk density may indicate overly loose structure, unstable aggregates, and rapid water loss beyond the root zone before plant uptake.

Surface litter accumulation showed a positive relationship with SOC content up to an optimal level between 230–250 g/m². Beyond this threshold, additional litter did not significantly increase SOC and may even slow decomposition due to imbalanced C/N ratios or limiting microclimatic conditions. This highlights the need for careful management of both the quantity and quality of litter inputs, particularly in cocoa cultivation systems on sloped land.

Table 1. Results of Soil Organic Carbon Analysis, Soil Physical Properties, and Surface Litter Dry Weight

Observation Point	Elevation (masl)	Texture (%)			Organic Carbon (%)	Bulk Density (g/cm³)	Saturated Hydraulic Conductivity (cm/hour)	Penetration Resistance (kPa)	Surface Litter Dry Weight (g/m²)
		Sand	Silt	Clay					
1	400	37.3	29.2	33.5	2.21	1.39	1.39	1,999.64	222
2		48	27.3	24.7	1.89	1.30	4.62	1,645.44	202
3		34.8	30.4	34.8	1.71	1.33	1.74	2,217.80	166
4	600	77.5	15.9	6,6	2.47	1.36	5.23	2,594.50	168
5		69.7	18.8	11.5	2.42	1.31	7.01	2,348.28	183
6		72.7	20	7.3	3.18	1.06	7.67	1,343.94	267
7	800	60.4	25	14.6	2.68	1.19	3.99	1,615.40	234
8		65.9	16.1	18	2.82	1.25	6.76	2,052.23	201
9		59	20.4	20.6	2.42	1.40	3.77	2,333.60	195

Decomposed organic matter has the ability to bind soil particles, resulting in loose, friable soil with good granulation, thereby reducing bulk density. Soils with higher organic matter content tend to be more friable and exhibit lower bulk density (Shi et al., 2016). The low organic matter content observed in agricultural lands can often be attributed to differences in land management practices. Soil organic matter in the form of litter—such as fallen leaves, twigs, flowers, and fruits—is generally more abundant in forested land than in intensively cultivated agricultural land (Durigan et al., 2017).

Clay-textured soils have a higher capacity to retain water, as finer soil particles provide greater surface area for water adsorption and storage (Basso et al., 2013). Organic carbon content also influences soil bulk density. In the present study, bulk density values ranged from 1.24 to 1.34 g/cm³, which falls within the medium category. Soils rich in organic matter generally have lower bulk density. Conversely, increased bulk density reduces soil water conductivity, whereas lower bulk density in less compacted soils enhances water movement (Vaccari et al., 2012).

The results of this study indicate that soil saturated hydraulic conductivity in the study area falls within the moderate to moderately rapid category. Variations in soil texture significantly influence hydraulic conductivity, with sandy soils typically exhibiting faster water transmission than clayey soils (Qi et al., 2022).

Soil penetration resistance in the study area is classified as high, with average values of 1,954; 2,095; and 2,000 kPa at elevations of 400, 600, and 800 masl, respectively. Differences in bulk density, organic carbon content, and texture across elevation zones influence penetration resistance. Human activities, particularly those related to land use and management, may also contribute to soil compaction at various depths (Durigan et al., 2017).

Soil functions as a medium for plant growth, and therefore requires a loose structure that allows easy root penetration. Soils with high penetration resistance often inhibit root development.

Analysis of surface litter dry weight revealed average values of 196.6, 206, and 210 g/m² at elevations of 400, 600, and 800 masl, respectively. The long-term accumulation of organic carbon suggests that agroforestry land use tends to store higher amounts of carbon and surface litter compared to annual cropping systems. In cocoa plantations, however, the presence of surface litter is strongly influenced by local land management practices and farmer behavior (Assefa et al., 2017).

Table 2 presents the polynomial regression statistical analysis of the relationships between soil organic carbon and physical properties in cocoa plantation areas within the study site.

Tabel 2. Polynomial Regression Statistics for Relationships Between Soil Organic Carbon and Selected Soil Physical Properties in Cocoa-Based Land-Use Systems

Relationship	F-statistic	p-value	Std. Error
SOC vs Bulk Density	12.78	0.007	±0.031
SOC vs Penetration Resistance	4.62	0.054	±227.8
SOC vs Hydraulic Conductivity	3.95	0.068	±1.21
SOC vs Surface Litter	5.24	0.041	±19.6
Bulk Density vs Penetration Resistance	8.92	0.014	±161.3
Bulk Density vs Hydraulic Conductivity	7.45	0.021	±1.79

The analysis of the relationship between soil organic carbon (SOC) content and bulk density revealed a quadratic pattern. An increase in SOC up to a certain threshold (approximately 3.0–3.2%) tended to reduce bulk density, which supports the role of organic matter in enhancing soil aggregation and porosity (Figure 1). However, there was an indication of rising bulk density after reaching an optimal point at approximately 2.13% SOC. This may be attributed to the accumulation of incompletely decomposed organic materials, where colloidal particles begin to fill micropore spaces.

The interaction between clay particles and organic matter did not significantly increase bulk density compared to the presence of organic carbon in sandy soils. However, when high levels of SOC are present in an undecomposed form, soils with silty-clay textures may experience a subsequent increase in bulk density (Thomazini et al., 2015).

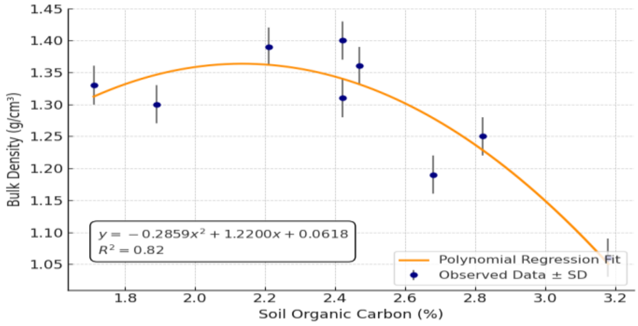

Figure 1. Relationship between soil organic carbon and bulk density.

The quadratic regression model ($R^2 = 0.82$) indicates a strong relationship between organic carbon content and bulk density. The initial decrease in bulk density with increasing SOC supports the beneficial role of organic matter in enhancing soil porosity and structure. However, beyond the optimal SOC range (2.1–2.2%), bulk density begins to rise again, possibly due to the accumulation of undecomposed organic materials that occupy micropore spaces, particularly in finer-textured soils.

The analysis of the relationship between soil organic carbon and penetration resistance revealed a peak at an organic carbon content of 2.27%, corresponding to a maximum penetration resistance of 2,228 kPa (Figure 2).

This pattern suggests that at low to moderate levels of organic carbon, penetration resistance tends to increase due to improved cohesion and aggregate stability. However, beyond the optimum point, further increases in organic matter content lead to a decrease in penetration resistance. This is likely due to enhanced porosity and the development of a looser soil structure.

These findings confirm that the influence of soil organic carbon on mechanical soil properties follows a quadratic pattern and highlight the importance of appropriately managing organic matter content in cocoa land-use systems.

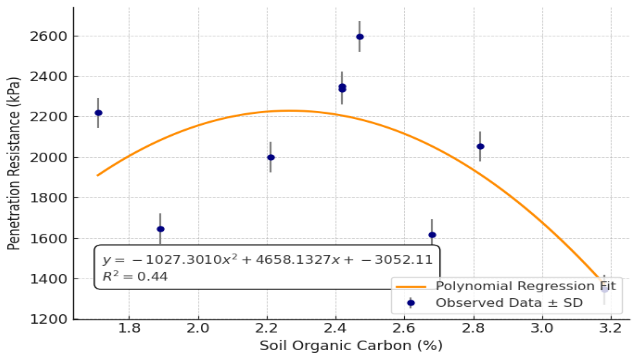

Figure 2. Relationship between soil organic carbon and penetration resistance.

The quadratic regression model ($R^2 = 0.44$) suggests a moderate curvilinear relationship between soil organic carbon (SOC) content and penetration resistance. The maximum penetration resistance of approximately 2,228 kPa occurs at a SOC content near 2.27%, indicating that low to moderate levels of organic carbon may enhance aggregate stability and cohesion, thereby increasing resistance. However, further increases in SOC content appear to reduce penetration resistance, likely due to increased porosity and the development of a more friable soil structure. While the relationship is not statistically strong, the trend supports the hypothesis that organic carbon influences soil mechanical behavior in a nonlinear fashion.

The results of this study indicate the occurrence of two contrasting yet complementary processes in soil behavior. First, the addition of organic matter contributes to increased aggregate strength, enhancing the soil's structural integrity. Second, rising organic matter content leads to greater porosity and reduced soil compaction. These opposing effects culminate in the existence of an optimum level of soil organic carbon that exerts the most beneficial influence on penetration resistance. Recognizing this nonlinear relationship is essential for effectively managing soil physical properties and maintaining stable soil structure, particularly in dryland agricultural systems. Excessively high levels of organic matter—especially in the form of undecomposed surface litter—tend to promote the formation of macropores and loose soil structures, thereby reducing soil resistance to external pressure as bulk density decreases (Shahgholi & Jnatkhah, 2018; Toková et al., 2020).

The analysis of the relationship between bulk density and saturated hydraulic conductivity revealed an increasing trend in hydraulic conductivity as bulk density decreased, up to an optimal point (Figure 3). This observation reflects the fact that lower bulk density is generally associated with higher total porosity, which facilitates the movement of water through soil pores. Conversely, soils with higher bulk density tend to be dominated by micropores, which restrict water flow and reduce overall hydraulic conductivity.

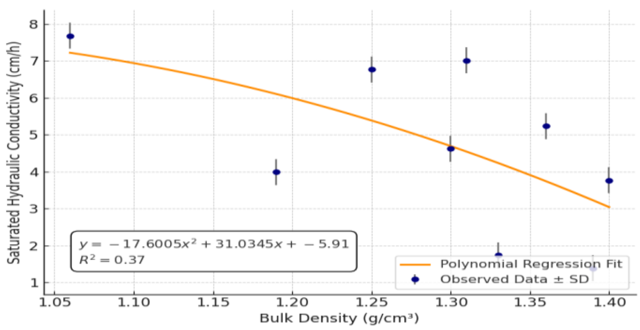

Figure 3. Relationship between soil bulk density and saturated hydraulic conductivity.

Figure 3 shows a quadratic relationship between soil bulk density and saturated hydraulic conductivity, with an R^2 value of 0.37, indicating a moderate level of association. The analysis reveals that as bulk density decreases, hydraulic conductivity tends to increase, reflecting improved soil porosity and structure that facilitate water movement through the soil profile. This trend supports the understanding that lower bulk density is typically associated with greater macropore space, enhancing infiltration rates. Conversely, higher bulk density suggests a predominance of micropores and possible soil compaction, which hinders water flow. Although the strength of the relationship is not strong, the observed pattern highlights the importance of managing bulk density to maintain optimal water conductivity, especially in sloped agricultural lands under cocoa cultivation.

When the soil bulk density approached approximately 1.06 g/cm³, saturated hydraulic conductivity reached its peak value of around 7.67 cm/hour. Beyond this point, further increases in bulk density led to a marked decline in hydraulic conductivity. This pattern suggests the presence of an optimal bulk density at which water movement through the soil profile is most efficient. Such a relationship is crucial for agricultural soil management, as both excessively high and overly low bulk densities can impair soil hydrological functions and overall productivity.

At elevated bulk density levels, soil porosity is predominantly composed of micropores, which restrict water infiltration and movement. This can lead to increased surface runoff and reduced water availability for plants, eventually contributing to long-term declines in soil productivity. Conversely, soils with excessively low bulk density tend to exhibit unstable structure, weak aggregate formation, and rapid water loss to deeper subsoil layers before root uptake can occur. This condition may result in localized drought stress in the root zone (Wang et al., 2009).

The analysis of the relationship between bulk density and soil penetration resistance revealed that approximately 62% of the variability in penetration resistance can be explained by variations in bulk density. The optimal point was observed at a bulk density of 1.99 g/cm³, corresponding to the maximum penetration resistance of 3,011.57 kPa (Figure 4). This result indicates a strong association between bulk density and the mechanical strength of soil, where increasing compaction enhances resistance to penetration up to a certain threshold. Understanding this relationship is essential for guiding soil management practices, particularly in relation to tillage intensity, compaction control, and root development in agricultural systems.

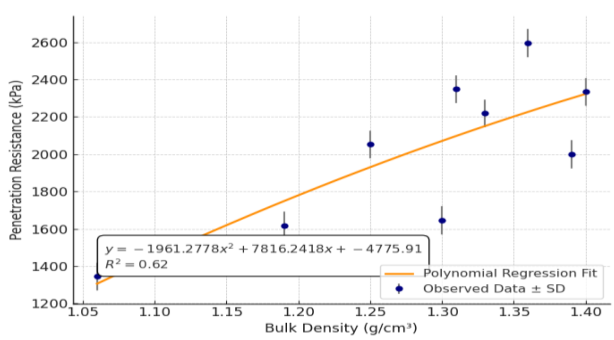

Figure 4. Relationship between soil bulk density and penetration resistance

Figure 4 presents a quadratic relationship between soil bulk density and penetration resistance. The analysis shows that approximately 62% of the variation in penetration resistance can be explained by differences in bulk density, as indicated by the coefficient of determination ($R^2 = 0.62$). The peak value of penetration resistance, 3,011.57 kPa, occurs at a bulk density of 1.99 g/cm³, suggesting that increased compaction enhances soil strength up to a critical point. Beyond this threshold, further increases in bulk density may not lead to proportional gains in mechanical resistance and could negatively affect root penetration and soil aeration. This relationship highlights the importance of maintaining optimal bulk density in agricultural soils to balance structural strength with biological function.

An increase in soil bulk density may reflect compaction processes that reduce total porosity, particularly the macropores essential for air and water movement (Robinson et al., 2022). Previous studies have shown that soils with higher levels of compaction tend to exhibit greater penetration resistance. This has important implications for land management, especially in conservation agriculture systems. High penetration resistance can serve as an indicator of physical constraints to root growth, as well as its influence on soil water and nutrient dynamics (Li et al., 2012).

The relationship between soil organic carbon content and penetration resistance indicates that penetration resistance increases with rising organic carbon levels up to an optimum point of 2.27%. Beyond this threshold, further increases in organic carbon content result in a decline in penetration resistance. This optimum point corresponds to a maximum penetration resistance value of 2,228.28 kPa (Figure 5). The observed trend suggests a nonlinear response of soil mechanical strength to organic matter enrichment, highlighting the dual role of organic carbon in enhancing soil aggregate stability while also increasing porosity under higher concentrations.

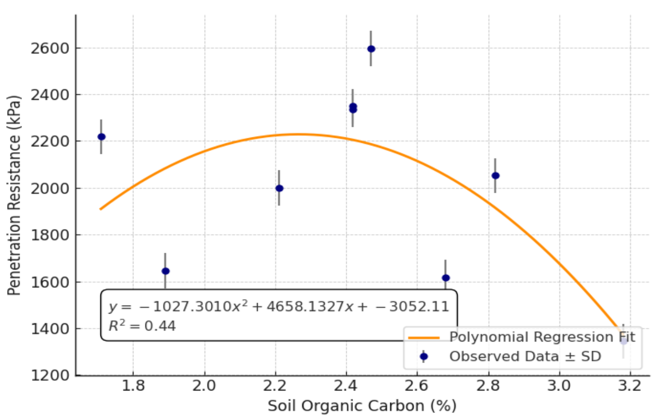

Figure 5. Relationship between soil organic carbon and penetration resistance

Figure 5 illustrates a quadratic relationship between soil organic carbon (C-organic) content and penetration resistance. The curve shows that as organic carbon increases, penetration resistance also rises, reaching a peak at an optimum C-organic level of approximately 2.27%, with a maximum penetration resistance of around 2,228 kPa. This pattern suggests that moderate levels of soil organic matter enhance aggregate stability and cohesion, thus increasing resistance to penetration. However, beyond this optimum point, further increases in C-organic content lead to a decline in penetration resistance. This may be attributed to the development of a more porous and friable soil structure, especially when undecomposed organic residues dominate, reducing the soil's mechanical resistance. These findings emphasize the need to manage soil organic matter within an optimal range to maintain favorable physical conditions in the root zone, which is particularly important in sloping land and conservation agriculture systems.

The curve describing the relationship between organic carbon and soil penetration resistance indicates that moderate levels of soil organic carbon contribute to the formation of a stable soil structure. However, at higher concentrations of organic carbon, the soil tends to become more friable or porous, which in turn leads to a reduction in resistance to mechanical pressure. This finding highlights the importance of managing soil organic matter within an optimal range to maintain ideal structural conditions in the root zone.

High levels of soil organic carbon contribute to the development of stable soil aggregates and enhanced macroporosity, both of which support the movement of air and water through the soil. This well-structured condition makes the soil more friable and easily penetrated by plant roots. Therefore, increased organic carbon content may result in reduced penetration resistance (Libohova et al., 2018).

The importance of considering soil organic carbon (C-organic) as a key variable in evaluating soil physical quality—especially in the context of critical land management—should be seriously addressed in future research. The addition of organic matter, apart from its role as a soil ameliorant, not only enhances chemical fertility but also improves soil structure, root development, and plant water-use efficiency. Litter, consisting of plant residues on the soil surface, plays a vital role in this process. As litter decomposes through microbial activity, it contributes directly to increasing soil organic carbon content. A higher dry mass of litter generally implies a greater potential for carbon accumulation in the soil, particularly under conditions of active decomposition.

The results of this study showed that C-organic content increased with higher litter dry mass, up to an optimum point. Beyond this point, further additions of litter no longer resulted in increased soil carbon levels, and in some cases, C-organic even declined despite additional litter inputs (Figure 6). This phenomenon can be explained by the decomposition dynamics of organic matter, which are influenced not only by the quantity of litter but also by the quality of organic material, microclimatic conditions, microbial activity, and soil texture. These factors collectively affect the rate of organic matter breakdown and mineralization (Frouz, 2018; Vaccari et al., 2012).

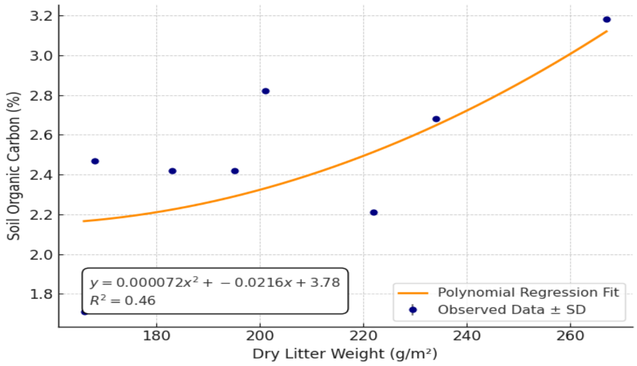

Figure 6. Relationship between litter dry weight and soil organic carbon

Figure 6 illustrates the relationship between litter dry weight and soil organic carbon (SOC) content. The graph shows that an increase in surface litter biomass is associated with a corresponding rise in SOC content up to a certain threshold. This pattern highlights the critical role of decomposed organic inputs in enriching soil carbon stocks. However, beyond the optimal litter accumulation point, SOC content tends to plateau or even decline slightly. This decline may occur when excessive litter inputs exceed the decomposition capacity of soil microbial communities, leading to slower mineralization rates or accumulation of partially decomposed organic matter. Additionally, environmental factors such as microclimatic conditions, litter quality, and soil texture may limit the efficient transformation of organic residues into stable soil carbon. These findings emphasize that not only the quantity but also the quality and turnover rate of surface litter are vital for enhancing and maintaining SOC in agricultural soils, particularly on sloped or degraded lands.

The optimum point, observed at a litter dry weight range of approximately 230–250 g/m², indicates that this level of surface litter accumulation represents the most efficient organic input for the formation of humus and stable soil carbon compounds. In contrast, excessive litter accumulation may lead to slower decomposition rates, likely due to an imbalance in the surface C/N ratio, which inhibits microbial activity. This relationship reinforces the importance of managing surface litter at optimal levels within cocoa cultivation systems on sloping land. Proper litter management is essential to support sustainable agricultural production while simultaneously improving soil quality through enhanced organic matter dynamics.

Elevation is one of the key ecological factors that influences the dynamics of organic matter input and accumulation on the soil surface. Variations in elevation are generally associated with changes in microclimate, particularly temperature and humidity, which in turn affect vegetation productivity, litter decomposition rates, and soil organic carbon (SOC) content. Overall, the results of this study indicate a general increase in SOC content with rising elevation, particularly when comparing lower elevation sites (400 m a.s.l.) to mid and upper elevations (600 to 800 m a.s.l.). This trend can be explained by several ecological mechanisms. First, lower temperatures at higher elevations slow down litter decomposition, allowing greater accumulation of organic residues on the soil surface. This ultimately leads to higher organic matter input, as evidenced by the slightly increased litter dry weight observed at 800 m compared to lower elevations. Second, higher elevations in this study tend to have denser ground cover vegetation and experience less anthropogenic disturbance, contributing to increased litter production and organic matter inputs. This condition is consistent with higher SOC values above 2.4 percent observed at these sites. Third, elevated areas typically receive more precipitation and maintain higher soil moisture, which favors the activity of soil microorganisms that facilitate the transformation of litter into stable soil organic compounds, enriching SOC pools over time.

The findings of this study reveal important linkages between SOC and various soil physical properties across different elevation levels within cocoa agroecosystems. However, some limitations must be acknowledged. The limited number of sampling points may not fully capture the spatial heterogeneity characteristic of sloping agricultural landscapes. Unmeasured variability in microclimate, understory vegetation, and land management practices outside the sampling sites may have influenced the results, thus limiting broader generalization. In addition, this study employed an observational, cross-sectional design, which does not account for temporal changes in SOC. Given that the accumulation and loss of soil organic matter are strongly time-dependent and influenced by seasonal biotic and abiotic interactions, longitudinal data would offer more robust insights. Furthermore, the data analysis focused primarily on bivariate relationships using polynomial regression, without exploring multivariate interactions or the combined effects of multiple soil variables.

For future research, it is recommended that studies be conducted across broader geographic areas with increased sampling replication and the incorporation of longitudinal approaches to better understand temporal dynamics in soil carbon. Additionally, the integration of spatial modeling and multivariate statistical techniques such as multiple regression can provide a more comprehensive understanding of the processes governing soil quality formation. These approaches could be further enriched by examining soil biological activity, including microbial biomass and soil respiration, to strengthen our understanding of carbon cycling in cocoa cultivation systems on sloped lands.

Conclusion

The results showed that SOC content tends to increase with elevation, particularly at 600 to 800 meters above sea level, which is attributed to cooler temperatures, denser vegetation cover, and reduced human disturbance, all of which favor greater litter accumulation and slower decomposition.

The study also found that SOC has a significant influence on key physical soil characteristics. A moderate increase in SOC improved soil structure, reduced bulk density, and enhanced saturated hydraulic conductivity. However, beyond an optimal SOC threshold (around 2.27–3.0%), additional organic inputs did not continue to improve, and in some cases slightly reduced, soil physical quality due to incomplete decomposition and potential pore clogging.

Furthermore, the relationship between surface litter accumulation and SOC content followed a curvilinear pattern, where increased litter contributed positively to SOC formation up to an optimal point. Excessive litter, however, may slow decomposition due to imbalanced C/N ratios. The findings emphasize the importance of managing organic inputs appropriately, especially in sloping cocoa landscapes, to ensure optimal soil conditions that support sustainable land productivity and carbon conservation.

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Author Contributions
Conceptualization: D.W., R.Z and F.R; methodology: D.W., R.S and F.R.; software, A.R.; validation, D.W., R.Z. and A.R; formal analysis, U.H.; investigation, R.Z. and R.G; resources, D.W. and M.A.K; data curation, R.S. and F.R.; writing—original draft preparation, D.W., R.Z. and F.R; writing—review and editing, M.A.K., U.H. and R.G.; visualization, R.G. and F.R.; supervision, D.W. and R.Z.; project administration, A.R. and F.R.

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Conflicts of Interest
The authors declare no conflict of interest.

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