RJOAS: Russian Journal of Agricultural and Socio-Economic Sciences
ISSN 2226-1184 (Online) | Issue 3(147), March 2024

UDC 633

SOIL CARBON STORAGE AND ERODIBILITY IN FOREST AND AGRICULTURAL LANDS: A CASE STUDY OF VOLCANIC PLATEAU OF MAS URAI MOUNT, JAMBI PROVINCE, INDONESIA

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ABSTRACT
Soil with high vegetation cover, such as forests, is the highest organic matter content and carbon storage, resistant to erosion, and a strategic component in mitigating and adapting to climate change. Encroachment and conversion of forests into agricultural land will reduce soil carbon stores (SCS) and its resistance to erosion due to the removal of SOM by erosion and oxidation. Muara Madras Village in Merangin Regency, Jambi Province is one of the areas whose forest is part of the Kerinci Seblat National Park, and part of it has been converted into agricultural land. The study aims to determine SCS and soil erodibility in forests and agricultural land in Muara Madras Village, conducted using an exploratory-descriptive survey method. Soil carbon stores are relatively no different between land uses with various slopes, 63.63-79.34 tons per hectare in forests, 66.05-78.91 tons per hectare in mixed farming, 72.72-76.63 tons per hectare in" tegalan". However, forest and mixed farming with a high slope (45-65 percent) have more SCS, 79.34 tons per hectare and 78.91 tons per hectare respectively. Soil erodibility is higher in mixed farming (0.11-0.36) and "tegalan" (0.27-0.29) than in forests (0.13-0.07). Mixed farming with a slope of 8-15 percent has the highest soil erodibility (0.36). It is necessary to control the negative influence of rainfall and topography on SCS and soil resistance to erosion through good and maximum soil surface cover with vegetation and plant residues.

KEY WORDS
Soil carbon stores, soil erodibility, forest, land agriculture.

The soil carbon (C) stock comprises of soil organic and soil inorganic carbon. Soil organic carbon (SOC) is the main component of soil organic matter (SOM) (FAO, 2017). Organic matter in mineral soils is generally only 2-10 percent, but its influence is significantly on soil quality (Bot and Benites, 2005), and SOM is one of the main factors that determine soil susceptibility to erosion (Wischmeier and Smith, 1978). Erosion is the main cause of soil degradation in wet tropical areas (such as Indonesia) due to high rainfall (Labriere et al., 2015). All types of erosion and a decrease in SOM content are land degradation processes that provide a direct response to climate change (IPCC, 2019). However, SOM is lost from soils both by oxidation in the process of decomposition and by erosion of topsoil. Some cultivated soils may over time lose as much as one-third to two-thirds of their original organic matter content (Hillel and Rosenzweig, 2009). Loss of SOM due to erosion is greater on agricultural land with plant beds in the direction of the slope (Henny et al., 2011). Maintaining

SOM content is crucial to protect soil and maintain SOC stores, which is increasingly important with climate change (Dariah and Maswar, 2014). Therefore, the status or level of SOM is an indicator of the sustainability of land resources or a land management system (Wolf and Snyder, 2003).

Soil organic carbon is dynamic and anthropogenic impacts on soil can convert it into a sink or source of greenhouse gases. Globally, SCS are estimated at an average of 1 500 Pg in the first meter of soil (FAO, 2017). The amount of SOC in land which is expressed as soil carbon stores (SCS, tons or Mg per hectare) depends on soil type, climate, topography, and land use or management (FAO, 2019). Soil carbon stores in dry land ranges from 20-300 tons per hectare and is mostly concentrated in the 0-30 cm layer (Agus *et al.,* 2011). Volcanic ash soil (Andosol or Andisol) contains huge carbon reserves per unit area (Tonneijck et al., 2010), notable for having the highest SCS capacity among the mineral soil orders in tropical climatic regimes with an average carbon stores of 25.4 kg C m^{-2} (Batjes, 2014). The potential of soils to sequester carbon is intimately associated with the content and nature of their clay fraction. Andisol covers only 0.8% of the earth's surface, but it contains approximately 1.8% of the global soil carbon (Hillel and Rosenzweig, 2009). This is because not only of vigorous vegetation growth due to the high fertility of the soils but of the high stability of the SOM against decomposition (Takahashi, 2020). Increasing SOC can be achieved through efforts such as maintaining high land cover with vegetation, increasing SOM content, and promoting tree populations for carbon sequestration (June and Sarvina, 2023).

Indonesia has diverse land uses, including forests, agroforestry, food estates, and monoculture agriculture like palm oil and rubber (Pagiola, 2000). Land use/land cover of Andisols is primarily native rainforest, tea plantation, horticultural crops, terraced paddy fields, and other food crops (Anda and Dahlgren, 2020). Natural forests are the highest carbon stock because of the high diversity of trees with undergrowth and lots of litter on the soil surface as the main source of SOM (Toru and Kibret, 2019). Deforestation can result in 20 to 50 percent loss of this stored C, largely through erosion (Eswaran *et al*., 1993). Therefore, the conversion of forests into agricultural land has a negative impact on SCS and soil erodibility (Arunrat *et al*., 2022). The vulnerability of soil separation to detachment by water is described as soil erodibility which can be affected by land use change (Jeloudar et al., 2018). In the Universal Soil Loss Equation, soil sensitivity to erosion is determined by the SOM, distribution of the very fine sand + silt and clay fraction, shape and size of the structure, and soil permeability (Wischmeier and Smith, 1978).

Deforestation in Indonesia also occurs in areas adjacent to forests, including protected forests in national park areas (Purba et al., 2014). Jangkat District, which is located in the volcanic plateau of Mount Masurai in Merangin Regency, Jambi Province, is one of the areas whose forests are part of the Kerinci Seblat National Park (KSNP) (Hartatik et al., 2005). However, forests in the area have been reduced due to deforestation in the 2010-2020 period, which has made way for agricultural land, especially mixed farming which is dominated by coffee plants (Prasetio, 2022). Coffee farming is the main source of income for people in Jangkat District. Most of the coffees farming areas are directly adjacent to conservation areas. As a result, encroachment on KSNP forests has become one of the factors causing forest destruction in Jangkat District, triggered by the trend of high-value coffee commodities. Jangkat District with high rainfall, steep slopes, and Andisol soil has a high potential for erosion and is prone to landslides (Sukarman and Dariah, 2014). Therefore, protecting and restoring forests and KSNP and controlling damage to agricultural land is crucial. Soil with its vegetation cover is a strategic component in mitigating and adapting to climate change and controlling soil degradation (Critchley et al., 2023). Tropical Andisols, whose high carbon stocks and several distinctive properties may differ in their response to land-use conversion (Anda and Dahlgren, 2020). The study aims to determine SCS and soil erodibility in forests and agricultural land in Muara Madras Village.

METHODS OF RESEARCH

Muara Madras Village with an area of 9964.1 ha is the capital of Jangkat District in Merangin Regency, ±138 km from Bangko City (regency capital), and ±256 km from Jambi City (provincial capital). Geographically, the village is located at 101º50'0''-101º58'0'' East and 2º36'0''-2º44'0'' LS, with an elevation of 1035 m above sea level (Figure 1). The climate in Muara Madras Village is classified as Type B (Q value = 0.197, wet) with an average rainfall of 2177.5 mm year^{-1} (176.0 mm/month), wet months 9.1, dry months 1.8, temperature and humidity 17.3°C and 51.9% respectively.

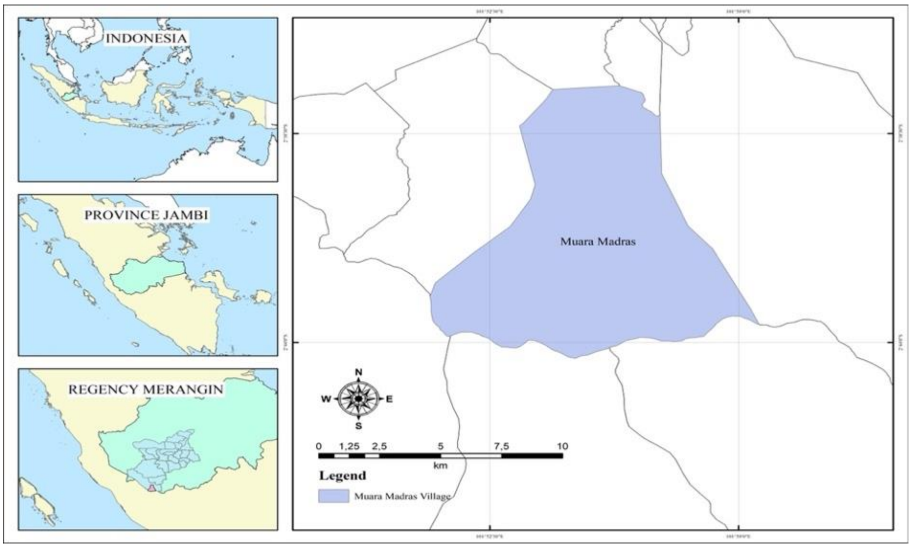

Figure 1 – Research Location at Muara Madras Village in Jangkat District, Merangin Regency, Jambi Province, Indonesia

The landform of Muara Madras Village is in the form of volcanic and tectonic plains of Mount Masurai, the rest is alluvial plains along the flow of the Mandras River (a tributary of the Batang Merangin River) and narrow valleys between the hills and mountains. The topography varies from flat to steep, most of it has a slope of >15% (hilly and mountainous to very steep topography), and most of the land use is forest. The Annual Report of the Agricultural Research and Development Agency of the Department of Agriculture in 2004 shows that the parent soil material in Jangkat District is dominated by old and young volcanic rocks. The soil is formed from young volcanic materials on the middle and lower slopes of Mount Masurai, classified as Hapludand (Hartatik et al., 2005). Hapludand is an Andisol with minimum horizon development and a rural humidity regime (never dry for 90 cumulative days per year) (Hardjowigeno, 2010).

The research was conducted using an exploratory-descriptive survey method. A work map of 1:75,000 scale was used to cover an area of 7861.3 hectares. Purposive stratified random sampling was used to determine the observation and soil sampling points. The number of soil sampling points for each homogenous land unit (HLU) was proportional to the area of that HLU, as shown in Table 1.

Table 1 – Homogeneous land unit (HLU) of survey area

Land use	Slope (%)	Wide (ha)
Forest	8-15	565.0
Forest	15-30	2430.0
Forest	30-45	2746.0
Forest	45-65	1737.0
Mixed farming	3-8	81.3
Mixed farming	8-15	83.6
Mixed farming	15-30	113.2
Mixed farming	30-45	60.0
Mixed farming	45-65	32.2
Tegalan	3-8	3.5
Tegalan	8-15	9.5

The data collected consists of primary data in the form of soil variables (depth 0-30 cm) as follows:

- Soil carbon stores (SCS), in tons per hectare were determined using soil organic carbon data (Walkley and Black Method), bulk density, 1 ha soil area (10^8 cm^2), and soil thickness (30 cm) using the formula:

$$SCS\ (g\ ha^{-}) = C - organic\ (\%) x\ bulk\ density\ (gcm^{-}) x\ 10^8 cm^2\ x\ 30\ cm$$

- Soil bulk density was determined for undisturbed soil samples heated up to105 ^{0}C:

$$Bulk\ density\ (BD) = \frac{Mass\ of\ solid\ soils\ (g)}{Soil\ volume\ total\ (cm^3)}$$

- Soil erodibility (K-factor in USLE; Wischmeier and Smith, 1978) was determined using data on the percentage of very fine sand, silt, and clay fractions (Pipette Method), soil organic matter (SOM), shape and size of soil structure (field observations and measurements), and soil permeability (De Boodt Method, based on Darcy's Law) with the following formula:

$$100\ K = 1{,}292\ [2{,}1 M^{1{,}14}\ (10^{-4})\ (12\text{-}a)\ + 3{,}25\ (b\text{-}2)\ + 2{,}5 (c\text{-}3)]$$

Where: M = (% very fine sand + % silt) x (% clay); a = SOM (%) = organic C (%) x 1.724; b = code of soil structure (Table 2); c = code of soil permeability (Table 2).

$$Soil\ permeability\ (cm\ h^{-}) = \frac{Q\ x\ L}{t\ x\ h\ x\ A}$$

Where: Q = volume of water flow (cm^3); L = height of sample ring (cm); T = time of measurement (hours); H = height of water surface from the surface soil sample (cm); A = wide of the surface soil sample (cm^2).

Table 2 – Code of structure and permeability of the soil

Class of soil structure (diameter measurement)	Code	Class of permeability	Speed (cm/hours)	Code
Very fine crumb and granular structure (<1mm)	1	very low	<0.125	6
Fine crumb and granular structure (1-2 mm)	2	Low	0.125-0.5	5
Moderate crumb and granular structure (2-5 mm) and coarse structure (5-10 mm)	3	moderate to low	0.5-2.0	4
Massive structure (prismatic, columnar, and blocky)	4	moderate	2.01-6.25	3
		moderate to high	6.25-12.5	2
		high to very high	>12.5	1

Source: Wischmeier and Smith (1978).

Data were analyzed descriptively using criteria for each variable from the available literature. The soil texture class was determined using the USDA Texture Triangle Diagram (Hardjowigeno, 2010). Soil erodibility was assessed using the value criteria in Arsyad (2010) (Table 3).

Table 3 – Criterion of soil organic carbon, bulk density, and erodibility

Organic C (%)	Criteria*	Bulk density (g cm^3)*	Criteria	Erodibility	Criteria**
<1	very low	<0.66	low	0.00-0.10	very low
1-2	low	0.66-1.4	medium	0.11-0.20	low
2-3	medium	>1.4	high	0.21-0.32	moderate
3-5	high			0.33-0.43	a bit high
>5	very high			0.44-0.55	high
				0.56-0.64	very high

*Source: *Centre of Soil research, Bogor (1994, in Hardjowigeno, 2010), **Arsyad (2010).*

RESULTS AND DISCUSSION

A variety of tree vegetation covers the forest in Muara Madras Village with a dense canopy with small plants under the trees and a lot and thick litter providing multiple and maximum ground surface cover (known as the "forest floor"). These forests are part of the protected forest area of KSNP and customary forest, as previously stated (Hartatik et al., 2005). However, some of these forests have been damaged by encroachment and logging on flat to hilly and mountainous topography, most often on slopes of 15-30 percent (hilly), as shown by patches of open land around the forest and logs that have been cut down. Farmers have reported that some of these forests have been converted into agricultural land, including mixed farming and “tegalan”. Meanwhile, undisturbed forest areas are still covered by tree vegetation with dense crowns (Figure 2).

Figure 2 – Forest condition on slopes of 15-30 percent (left) and 60 percent (middle and right) in Muara Madras Village

Mixed farming practices in Muara Madras Village are planted with various perennial crops (coffee, cinnamon, tobacco). Still, the dominant commodity is Arabica coffee. At the same time, cinnamon and tobacco are only a sideline among coffee plants and on the outskirts of mixed farming and tegalan, as well as land boundaries between farm owners. Coffee planting distances vary on flat, hilly, and mountainous land, but mostly on land with a 15-30 percent slope.

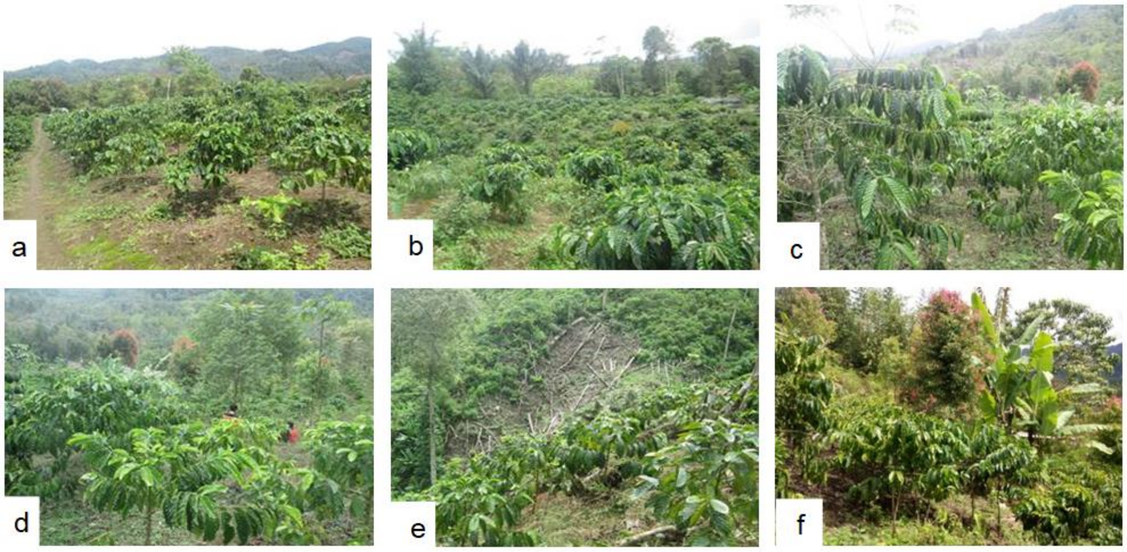

Figure 3 – Mixed farming with slopes of 3-8 (a), 8-15 (b), 15-30 (c), 30-45 (d), >45 percent (e), and cinnamon as farm boundary (f) in Muara Madras Village

The growth of some coffee plants was not good enough because farmers did not fertilize their coffee plants. The soil was covered with litter from fallen coffee leaves and weeds among the plants. Thus, they think the soil is fertile. However, farmers do weeding on farms with a slope of <15% because it is quite close and easy to reach from home, while on other land (slope >15%), no weeding is done. Some coffee plants grow well, and the soil surface is relatively clean (only covered by a few weeds) with intercrops as shade for coffee plants, but the number is small compared to the coffee farm area. Good crop conditions are indicated by dense plant canopies, especially on land with a slope of 30-45 percent (Figure 3).

"Tegalan" in Muara Madras Village is land planted with annual crops, potatoes and chilies as the main crops (other crops are sweet potatoes, long beans, corn, and cucumber). Potato farms are primarily on land with a slope of 8-15 percent, with planting patterns generally potato-potato-potato and potato-potato-chili. The plant bed or rows of potato, chili, and other annual crops align with the slope, not under soil and water conservation principles. Chilies are planted using plastic mulch to maintain soil moisture and control weed growth (Figure 4a, 4b). Farmers conduct fertilization (Urea, KCl, and TSP) and weed removal. Andisol soil which is easily eroded and has many open soil surfaces will accelerate and increase the destructive power of raindrops and surface runoff so that it can increase erosion and sediment in rivers. The flow of the Madras River is usually swift because the height difference between upstream and downstream is quite significant. Hence, the possibility of sedimentation in the river body is very small. However, the river water looks clear only when there is no rain. In contrast, after rain, the water turns brown due to sediment load from eroded soil in the upstream area (Figure 4c, 4d).

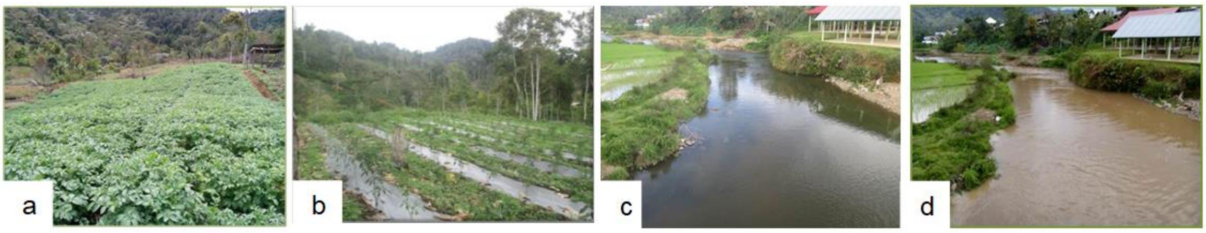

Figure 4 – Tegalan with potato crops on 6% percent slope (a), chilli crops on 12% percent (b), and Mandras River flow before (c) and after rain (d) in Muara Madras Village

The soil texture classes vary from silty loam (medium) to silty clay loam (rather fine) in forest soils, loam (medium) to silty clay loam (rather fine) in mixed farming soil, and silty loam (medium) in tegalan soils. The distribution of soil fractions is dominated by the silt fraction in both forest soils (45.26-61.98 percent), mixed farming (45.80-67.57 percent), and tegalan soils (48.72-50.39 percent); relatively not different, but the percentage of clay is slightly higher in forest soils (Figure 5) as is the general Andisol soil texture. Analysis of Andisols from various regions in Indonesia shows that Andisols have textures varying from clayey (30-65 percent clay) to coarse clay (10-20 percent clay). Still, most are classified as fine loamy to coarse loamy (Hidayat and Mulyani, 2002). The composition of clay and sand fractions that are not too large is one of the characteristics that can be found in Andisols because these soils have unique physico-chemical properties and mineral composition, which are generally loose with a medium texture (dominance of silt) (Suratman et al., 2018). Soils developed from volcanoclastic materials involve diversity in soil classification and properties (Takahashi, 2020). Andisol soils with volcanic ash parent material are generally dominated by the silt fraction which is easily eroded because having a relatively fine fraction and also cannot form bonds (without the help of adhesives/binders), because it has no charge (Dariah et al., 2004).

Soil texture in forest and mixed farming tended to become finer with steeper slopes, especially at slopes >15% (Figure 2). This is due to relatively less erosion despite the steeper slopes on these fields due to higher ground cover by the canopy, plant debris, and litter compared to fields with slopes <15%. Good ground cover vegetation, such as thick grass or dense jungle, will eliminate the influence of rain and topography on erosion (Arsyad, 2010). This shows that soil texture is one of the soil property variables that is not affected by management and determines soil quality, unchanging, permanent, or inherent (Islam and Weill, 2000). However, if the land is sloping and the land surface is exposed, then the soil texture can change due to soil being carried away by erosion, and erosion is selective. Finer soil fractions are carried away first and more; as a result, the eroded soil has a higher percentage of sand (Troeh et al., 2004).

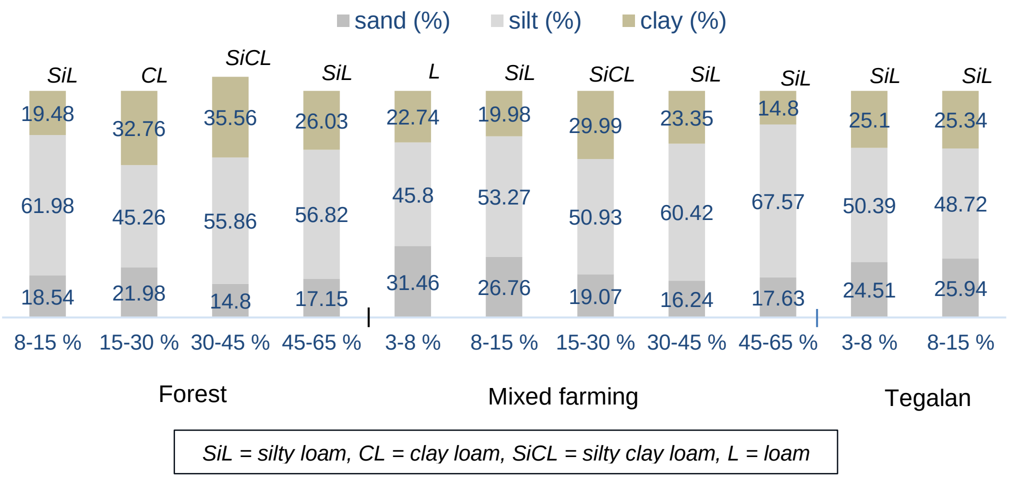

Figure 5 – Distribution of sand, silt, and clay fractions and texture classes of forest soils, mixed farming, and tegalan on a slope of 3-60 percent in Muara Madras Village

Forest soil carbon stores (SCS) is greater (5.05-6.15 percent, classified as very high) than that of mixed farming (4.34-5.48 percent, classified as medium to very high), and tegalan (4.04-4.12 percent, classified as high) (Table 4). High to very high SOC of Andisol in Muara Madras Village shows that volcanic soils are characterized by their ability to retain SOC because volcanic ash materials contain dark-colored, non-crystalline (short-range-order) high-organic carbon minerals. The carbon organic content of Andisol soil in Indonesia varies from 1.24 to 22.46 percent and there is a decrease in the C-organic content of Andosol soil due to its use for plantations or horticultural crops (Sukarman and Dariah, 2014). Soil organic carbon plays a key role in the structural stability of soils and their resistance against erosion (Rodrigues et al., 2006).

Soil organic carbon was highest in the forest with a slope of 45-65 percent (Table 4). This is because these forests have more diverse vegetation with a variety of tall and large trees (tree diameter > 50 cm) to low and small plants, resulting in denser and denser crowns and thicker litter and providing more additional organic matter to the soil compared to forests with less steep slopes (15-40 percent slope). Forests with dense canopy and soil surfaces covered with litter and organic matter play an essential role in protecting the soil from rainfall and maintaining the quality and fertility of forest soil. Falling leaves stems, twigs, fruits, and flowers that decompose in forest soils help to increase SOC, thus providing good soil physical properties and increasing soil nutrient availability. Lower temperatures and higher humidity can cause the high SOC content in forests with steeper slopes due to the dense canopy and sunlight not directly penetrating the soil surface, so the weathering process in forest soils takes place more slowly. High humidity and low temperature make forests very important in maintaining the balance and continuity of organic matter supply in leaf litter, fruit, or wood litter (Agus et al. 2004). As a large proportion of organic matter is present in the top (especially in 0-10 cm of soil), protecting the soil surface from erosion is central to retaining soil organic matter. Management practices also have a significant influence on whether actual SOM (and carbon) reaches its attainable level as determined by climate. Organic matter decomposes more slowly as temperatures decline, under moist conditions each 10^0C increase in temperature doubles the rate of organic matter decomposition. This means moist, warm conditions will often result in the most rapid decomposition of SOM (Hoyle, 2013).

Table 4 – Soil organic carbon, shape and size of structure, bulk density, and permeability of soil forest and agriculture land in Muara Madras Village

Land use types (slope, %)	SOC (%)-*criteria*	BD (g/cm^3)-*criteria*	Permeability (cm/h)-*criteria*
Forest (8-15)	5.81 *very high*	0.41 *low*	13.06 *moderate-high*
Forest (15-30)	5.41 *very high*	0.46 *low*	10.11 *moderate*
Forest (30-45)	5.05 *very high*	0.42 *low*	8.32 *moderate*
Forest (45-65)	6.15 *very high*	0.43 *low*	13.98 *moderate-high*
Mix farming (3-8)	4.34 *high*	0.55 *low*	6.00 *low-moderate*
Mix farming (8-15)	4.36 *high*	0.59 *low*	6.03 *low-moderate*
Mix farming (15-30)	5.12 *high*	0.53 *low*	7.64 *moderate*
Mix farming (30-45)	5.31 *high*	0.59 *low*	8.32 *moderate*
Mix farming (45-65)	5.48 *very high*	0.48 *low*	8.36 *moderate*
Tegalan (3-8)	4.12 *high*	0.62 *low*	4.66 *low-moderate*
Tegalan (8-15)	4.04 *high*	0.60 *low*	2.84 *low-moderate*

The soil organic carbon content in tegalan (land used for vegetable horticulture) is lower, with an average of 4.08%, when compared to mixed farming (average 4.96%) and forest soil (average 5.61%) as shown in Table 4. This difference in SOC content can be attributed to the land processing method used in tegalan, which involves land preparation at each crop cycle and leaves the surface of the land more exposed. The process of tilling structured soils reduces the amount of soil organic matter (SOM) stocks due to the exposure of organic matter to microbial decomposition (Hoyle, 2013). Research shows that complete tillage (primary and secondary) using a hoe or plow with a tractor can lead to a 36.94% reduction in SOC content after four weeks of processing, with a concurrent increase in soil bulk density as SOM content decreases (Henny et al., 2021; Faharani et al., 2022). However, the reduction in SOC content can be controlled by following soil processing with the application of organic fertilizer and planting vegetation with maximum canopy cover to protect the soil surface (Henny et al., 2024; Henny and Arsyad, 2022).

High SOC resulted in low soil BD in both forest soils (0.41-0.46 g cm^{-3}), mixed farming soils (0.48-0.59 g cm^{-3}), and tegalan (0.62-0.6 g cm^{-3}) (Table 4). The bulk density of Andosol in Indonesia varies from 0.37 to 0.90 g cm^{-3} (Table 10). The low BD of Andisol cannot be separated from the influence of the dominant amorphous mineral (allophane) content so the number of micropores is quite large, especially the intra and inter-particle pores of allophane (Sukarman and Dariah, 2014). Low BD values are one of the characteristics of soils formed from volcanic ash, which are porous, because they are influenced by the content of amorphous minerals and organic matter (Sukarman et al., 2020). However, BD tended to be higher in agricultural land, and highest in tegalan, lowest in forest land. There is an inverse relationship between SOC and BD, which is an indicator of soil density; the higher the SOC, the lower the BD of the soil, which means that soils in tegalan tend to be slightly denser than forest and mixed farming soils. However, soil BD is still relatively low because SOC is still relatively high. This shows that high organic carbon can reduce the negative effects of tillage. Soil permeability tends to be faster in forest soils and slower in tegalan. The high organic carbon and low BD result in better pore space and thus faster soil permeability in forest soils (8-32- 13.98 cm h^{-1}), whereas permeability is lowest in tegalan (2.84-4.66 cm h^{-1}) because of higher BD due to lower SOC (Table 4). Soil permeability is influenced by texture, structure, porosity, BD, and viscosity of liquid (Troeh et al., 2004).

Soil carbon stores (SCS) did not differ relatively between land uses with varying slopes in the range of 63.63-79.34 tons ha^{-1} in forest, 66.05-78.91 tons ha^{-1} in mixed farming, and 72.72-76.63 tons ha^{-1} in tegalan. However, soils in forests with the highest slopes (45-65 percent) had the highest SCS (79.34 tons ha^{-1}) and were relatively the same as SCS in mixed farming (78.91 tons ha^{-1}). While SCS in tegalan is relatively the same on slopes of 3-8 and 8-15 percent respectively (Table 4). These SCS are different from Arunrat et al. (2022) who found SCS in natural forests (0-100 cm depth) of 174.4 Mg C ha^{-1} reduced to 82.7 Mg C ha^{-1} (52.5% lost) after conversion to corn land. In the case of Muara Madras Village, land cover by vegetation, undergrowth, plant residues and litter in mixed farming dominated by coffee plants is still quite high, farmers do not eradicate weeds, except in areas adjacent to residences.

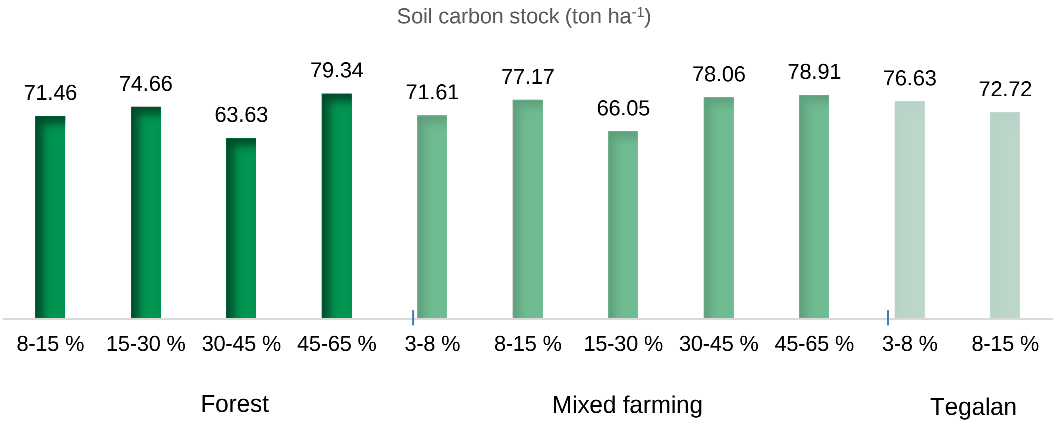

Figure 6 – Soil carbon stock in forests, mixed farming, and tegalan with various slopes in Muara Madras Village

The high SCS in forests with 45-65 percent slope was caused by the highest SOC content (6.15%) and lower in BD (0.43 g cm^{-3}) (Table 4) due to high land cover by diverse tree vegetation and undergrowth as well as abundant and thick litter, as explained previously. Maximum vegetation cover provides maximum protection for the soil surface from decreasing SOC through erosion and controls the speed of the decomposition process of organic material by soil organisms. In this way, the soil's ability to absorb and pass rainwater (infiltration) and surface runoff is also maintained. The amount of SCS in mixed farming with the same topography but lower SOC (5.48 %), is also high and relatively no different from SCS in forests due to the slightly higher soil BD (0.48 g cm^{-3}) in mixed farming. This condition also explains why SCS is also high in mixed farming with a slope of 30-45 percent, with a SOC of 5.31% and a slightly higher bulk density (0.59 g cm^{-3}). Farmers let wild plants, crop residues, and litter cover the land below standing coffee plants. In contrast to other forest and mixed farming (especially with slopes of 30-45 and 15-30 percent respectively), lower SOM and higher BD provide slightly lower SCS due to more land surface being exposed by forest encroachment, and weeding of mixed agricultural land from weeds or undergrowth carried out by farmers, because of its position close to residential areas. Open soil surfaces accelerate the oxidation process in the decomposition of organic material, and erosion carries topsoil which generally has higher organic matter, as explained previously. This further shows that land cover with good vegetation and maximum plant residue can eliminate the negative influence of rain and topography on the sustainability of the soil's function in storing carbon, and vice versa (Arsyad, 2010).

Soil organic carbon stock in the forest in this study is lower than natural forest research results by Toru and Kibret (2019) in sandy clay soil at depths of 0-20 cm and 20-40 cm (141.34 tons and 101.36 tons C ha^{-1}), with higher in BD (0.91 and 1.09 g cm^{-3}). Meanwhile, SCS coffee agroforestry has 93.78 tons and 81.07 tons C ha^{-1}) with the same soil class texture but higher SOC and lower BD. In contrast, SCS on agricultural land with food crop commodities (53.11 tons and 48.81 tons C ha^{-1}) was lower with much higher BD and lower SOC compared to vegetable horticulture land in this study. This shows that SCS depends on soil texture as one of the soil characteristics that influences SOC soil BD, and land use or vegetation cover including soil management.

Soil erodibility which is classified as very low to low in forests and mixed farming (0.07-0.15) is more caused by the SOM and clay fraction, which is relatively higher (10.60-8.29 percent) in forest and mixed farming soils compared to in mixed farming with slopes of 3-8 and 8-15 percent and dry land (7.52-6.96 percent) with soil erodibility classified as moderate to a bit high (0.26 to 0.36) (Table 5).

Soils with more silt very fine sand fractions are most sensitive to erosion (Hardjowigeno, 2010) due to uncharged and loose, so they are easily carried away by surface flow; the higher the silt content in the soil, the more sensitive to erosion (Dariah et al., 2004). In this case, the influence of the high distribution of very fine sand + silt can be controlled by the high SOM and clay fraction so that it also provides a good soil structure (granular, fine with fine to coarse sizes). As mentioned previously, the value of soil erodibility (K factor) in the USLE is the collective influence of the distribution of soil fractions (very fine sand + silt, and clay), SOM, and soil permeability on the resistance of soil aggregates to the impact of raindrops and the transport of sediment to surface flow (Wischmeier and Smith, 1978). The high content of SOM in Andisol soils with volcanic ash parent material creates a good soil structure with a granular and fine soil structure size, which is consistent across all land uses and slopes. The accumulation of soil SOM is a characteristic property of Andosols. A large accumulation of organic matter results from a combination of high detritus input associated with the high fertility of Andosols and from the effective stabilization of SOM against decomposition (Takahashi, 2020).

Table 5 – Distribution of very fine sand, silt, and clay fractions, organic matter, and erodibility of forest soils, mixed farming, and tegalan in Muara Madras Village

Land use types (slope, %)	Soil fraction distribution (%)		SOM (%)	Shape, size-code of soil structure	Criteria of soil permeability-codes	Soil erodibility-criteria
	very fine sand + silt	clay				
Forest (8-15)	66.76	19.48	8.29	granular, f-2	moderate, fast-2	0.07 [very low]
Forest (15-30)	50.35	32.76	7.60	granular, f-2	moderate-3	0.13 [low]
Forest (30-45	58.96	35.56	8.71	granular, f-2	moderate-3	0.11 [low]
Forest (>45)	61.02	26.03	10.60	granular, f-3	moderate, fast-2	0.09 [very low]
Mix farming (3-8)	54.07	22.74	7.48	granular, f-2	low, moderate-4	0.26 [moderate]
Mix farming (8-15)	61.41	19.98	7.52	granular, f-2	low, moderate-4	0.36 [a bit high]
Mix farming (15-30)	56.05	29.99	8.83	granular, f-2	moderate-3	0.11 [very low]
Mix farming (30-45	64.95	23.35	9.15	granular, f-2	moderate-3	0.13 [low]
Mix farming >45	72.61	14.80	9.45	granular, f-2	moderate-3	0.15 [low]
Tegalan (3-8)	59.46	25.10	7.10	granular, f-2	low, moderate-4	0.29 [moderate]
Tegalan (8-15)	55.46	25.34	6.96	granular, f-2	low, moderate-4	0.27 [moderate]

The fine fraction of soil in the form of very fine sand and silt which has no charge, is carried away more easily and first by surface flows because erosion is selective. Meanwhile, the clay fraction which is cohesive and sticky together with SOM plays a role in increasing soil resistance to the destructive energy of raindrops and surface flow, thereby producing stable aggregates, maintaining porosity and soil permeability or water movement in the soil (soil is more resistant to erosion). Therefore, soil with a high distribution of fine fractions (very fine sand + silt) is sensitive or easily eroded, but if the clay fraction and SOM content are high it can provide high soil resistance to erosion. Djuwansah and Mulyono (2017) also found that soil erodibility is largely determined by very fine sand + silt and SOM, and Wang et al. (2013) found that the SOM and clay contents are the principal factors that influenced soil erodibility. Wischmeier and Mannering (1969) also concluded that the most influential indicators of erodibility were particle size distribution and organic matter content. This finding is supported by Neris et al. (2013) that the protective effect of the organic covering and how the stability of the Andisols helps combat water erosion processes. The research results of Jeloudar et al. (2018) in Typic Haploxerepts soil showed that soil erodibility is affected by permeability and organic matter, the K-factor has a negative and significant correlation with organic matter and permeability.

Table 5 also shows that soil erodibility in mixed farms on slopes of 3-8 percent (0.26) and slopes of 8-15 percent (0.36) is much greater than soil erodibility on land with slopes >15%. This suggests that agricultural land use and management decreases soil resilience or increases its sensitivity to erosion, due to a more exposed soil surface with less vegetation cover. Land use type can impact soil properties and the characteristics of the plant community, which in turn likely affect soil erodibility (Chen et al., 2023). There was a significant relationship between erodibility and soil physical properties for the various soil conservations. Nevertheless, across the entire soil conservation measures, silt and BD were significantly correlated with erodibility (Ojo et al., 2023).

CONCLUSION

Soil carbon stores are relatively no different between land uses with various slopes (63.63-79.34 tons ha^{-1} in forests, 66.05-78.91 tons ha^{-1} in mixed farming, 72.72-76.63 tons ha^{-1} in tegalan). However, forest and mixed farming with a high slope (45-65 percent) have more SCS, 79.34 tons ha^{-1} and 78.91 tons ha^{-1} respectively. Soil erodibility is higher in mixed farming (0.11-0.36) and in tegalan (0.27-0.29) than in forests (0.13-0.07). Mixed farming with a slope of 8-15 percent has the highest soil erodibility (0.36). It is necessary to control the negative influence of topography on SCS and soil resistance to erosion through good and maximum soil surface cover with vegetation and plant residues.

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