Organic carbon sequestration at gambier (Uncaria gambier L.) cultivation in sloping area under wet tropical region

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Abstract. Organic carbon (OC) is an important factor for soil and the environment. This research aimed to identify OC sequestration under different age of gambier crops in central Gambier, Pesisir Selatan, West Sumatra. Soil samples were taken from different crop ages (2, 5, and 10 years old), and then under secondary forest nearby as a comparison at 0-30 cm soil depth. The results showed that, in general, soil OC content was considered low to very low either under Gambier crops (<2%), or under forest land use (2.1%). Then, the OC stock increased by increasing crop age from 2 to 10 years old. The OC stock at ten years old Gambier reached 90% of that at the forest on the top 30 cm soil depths. Rate of OC sequestration was approximately 1.03 Mg ha⁻¹ y⁻¹ and 4.88 Mg ha⁻¹ y⁻¹, respectively, for crop age between 2 and 5 as well as between 5 and 10 years old. This low soil organic carbon (SOC) content combined with fine soil particles caused the soil had medium-high soil BD, low-medium total soil porosity, rather slow-medium hydraulic conductivity rate, and unstable-rather stable soil aggregate stability. The study concludes that SOC sequestration under Gambier plantation in the sloping area was quite slow, especially during the first five years due to new crop establishment and the leaves harvested.

1. Introduction

Organic carbon sequestration is important to improve environmental quality, either to improve soil quality as well as to mitigate CO₂ emission to the atmosphere. Organic C sequestration in the soil will decrease carbon concentration in the atmosphere causing global warming. Nowadays, emission of CO₂ increased by 146% from 1750 (278 ppm) to 2017 (405.5 ppm) due to anthropogenic activities [1], which had already caused ~1°C increased in global temperature [2]. Increasing OC sequestration in the soil will improve either the environment as well as soil properties.

There is a positive relationship between OC stock and soil physical properties [3], especially soil aggregate stability [4]. The decrease in SOC would impact an increase in soil erodibility, soil susceptibility, and surface crust formation (Pellegrini et al., 2018). Intensive land cultivation in Padang city under wet tropical regions decreased the SOC content [5]. Land-use change from mix garden into seasonal crop farming decreased SOM by 61.5% (from 2.65 into 1.03%). Decreasing OC stock by 6.3% in Andisols caused in higher soil loss by 4.6%. Soil aggregates >0.053 mm could potentially associate with OC, which might increase OC sequestration in soil under long-term cropping system [6]. It was suggested to incorporate organic materials into the soil to maintain and improve soil physical properties, especially soil structure, water retention, as well as drainage capacity during crop growth [7].
Dynamics of OC in the soil is dependent upon the management and climate condition [8]. They found that it was about 58% of the SOC was the loss in wet tropical soils due to long term management. It was about 63.7-71.7% OC within tot C in the soil for 100 cm soil profile, and 44.2-49.5% of the OC was found on the upper 30 cm soil depth [9]. On the other hand, change in tillage system from conventional to conservation type and enhancement of crop rotation could sequester SOC about $57 \pm 14 \text{ g C m}^{-2} \text{ yr}^{-1}$ and $20 \pm 12 \text{ g C m}^{-2} \text{ yr}^{-1}$, respectively [10]. Then, it was reported that tillage method, temperature, and soil water content affected the amount of CO$_2$ released to the atmosphere [11].

Some factors could be done to increase OC sequestration in cultivated soil, such as planting cover crops [12], improving soil management [13], fertilizing land [14, 15, 16]. Some factors controlling SOC accumulation and stabilization were clay particles, parent materials, as well as climate and vegetation [17]. Miscanthus, as a shade tree in the plantation, was also reported that it could contribute 0.6 Mg ha$^{-2}$ yr$^{-1}$ OC to the OC pool in the tropical region, Puerto Rico [19].

Conservation agriculture is suggested to reduce CO$_2$ emission, application biochar, agroforestry system, integrated farming, recycling biomass at all-region (local, regional, national, and international) [20]. Smart agriculture, such as no-till cultivation, crop establishment, residue management, and crop diversification, could improve SOC sequestration [21]. Then, conservation management systems such as reduced- and no-tillage, crop residue addition, farmyard manure incorporation, and integrated nutrient management increased SOC accumulation and improved the sustainability of agricultural systems [22]. Gonzalez-Sanchez et al. [23] reported that conservation agriculture in Africa could sequester OC in soil up to 143 Tg yr$^{-1}$, which was much higher than the sequestration data nowadays. The information on the initial condition and the previous management of the soil is needed to predict the amount of SOC sequestration in soil [24].

2. Materials and Method

This research employed a survey method on which the samples were taken based on purposive sampling. Soil samples were taken in one of Gambier production center in West Sumatra, that was in Lansano, Pesisir Selatan Regency. The area was located between 100°30'- 100°57’ E and 1°30'-1°39’S, having altitude 2 - 150 m above sea level (asl). The area had high annual rainfall (2,659 mm) with average 221.6 mm/month and had the Q value = 0.034. Therefore, based on Smith and Fergusson [25], the research location belonged to wet area (A type climate). The soil order in the research site was dominated by Inceptisols.

Area for sampling was divided into 4 land units (three land units were under Gambier cultivation and the other was under forest land use as comparison). Land unit was resulted from overlaying 3 types of map those were land use (Gambier crops and forest ), soil order (Inceptisols), slope (15-25%). The soil was sampled from 3 different Gambier ages (2, 5, and 10 years old of Gambier). Then, as a comparison, soil was also sampled from secondary forest nearby at the same slope and soil order. Three sampling points were randomly determined from each land unit, and each sampling point was composited from 5 different sub locations for disturbed soil samples. Undisturbed soil samples for determining soil bulk density (BD), total soil porosity, and soil hydraulic conductivity were taken using soil ring having 7.5 cm in diameter and 4 cm in height. All of the soil samples were processed and analyzed at soil laboratory, Andalas University Padang, Indonesia.

Soil bulk density and total porosity were determined by gravimetric method, while soil hydraulic conductivity was measured using constant head permeameter based on Darcy’s law. Then, disturbed composited soil samples were air-dried, ground, and then sieved using 2 mm sieve to separate between soil and non soil materials. The 2-mm gound soil samples were used to measure the water content and to analyze soil texture. Then, the 2-mm soil particles were further ground to pass 0.5 mm sieve for soil OC analyses. Wet oxidation [26] method was employed to determine the OC content. Organic carbon stock at soil was calculated based on Yulnafatmawita and Yasin [5]:
SOC Stock (Mg ha⁻¹) = %OC/100 x ρb x d x 10,000 m² ha⁻¹

SOC = soil organic carbon
OC = organic carbon content
ρb = soil bulk density or BD (Mg m⁻³)
d = soil depth (m)

Then, soil organic carbon sequestration rate was calculated based on the following formula:

SOC Sequestration rate (Mg ha⁻¹ y⁻¹) = \left(\frac{OC \text{ Stock}_{\text{end}} - OC \text{ Stock}_{\text{initial}}}{\text{Age}_{\text{end}} - \text{Age}_{\text{initial}}}\right) \text{Mg ha}^{-1} \text{ y}^{-1}

OC Stock_{\text{end}} = Organic carbon stock at older crop age (Mg ha⁻¹)
OC Stock_{\text{initial}} = Organic carbon stock at younger crop age (Mg ha⁻¹)
Age_{\text{end}} = Age of older crop (y)
Age_{\text{initial}} = Age of younger crop (y)

3. Results and Discussion

3.1 Soil Organic Carbon Sequestration

Organic carbon (OC) sequestration on the top 30 cm soil depth either under Gambier plantation at all ages or under forest land use was presented in Figure 1. The amount of OC sequestered on the top 30 cm soil depth under gambier was considered low. This could be due to low contribution of the crop residue to the soil, as the crops leaves are harvested. Therefore, the litter derived from the crop leaves and small branches are almost none. Soil OC decreased by time following land use change from grassland to agriculuture land. This was mainly found during the first 5 years of crop age, before it was well established [27].

Figure 1. Organic carbon sequestration on the top 30 cm soil depth under different age of Gambier and secondary forest

Then, the amount of OC sequestered in the soil increased by time as the crop age increased from 5 to 10 years old. This seemed to be caused by the crops that had been established, and some understorey plants had grown well and contributed to SOC. Furthermore, no cultivation for the soil during the crop growth as well as returning the leaves residue after being pressed has accumulated the OC in the soil by time. Soil OM storage increased under tea plantation in sloping area as the crop became mature [28].
3.2 Rate of Organic Carbon Sequestration
Rate of OC sequestration at Gambier cultivation in sloping area under wet tropical region was lower during the first 5 years (2-5 years old) than that during the second 5 years (5-10 years old) on the top 30 cm soil depth. Soil OC stock only increased by 9% in three years (2-5 years old crops), and then increased by 66% in the following 5 years (5 to 10 years old crops). This could be due to the effect of crop growth progress, on which the Gambier crops had been established after 5 years old. Therefore, the rate of OC sequestration at the second 5 years became faster because the amount of OC derived either from the root exudates or from the understorey plants became higher. As provided on Table 1, the SOC sequestration rate on the top 30 cm soil depth was only 1.03 Mg ha⁻¹ y⁻¹ between 2-5 years, and then it increased into 4.88 Mg ha⁻¹ y⁻¹ between 5 and 10 years old of crop age. Soil OC sequestration rate was 0.43 Mg ha⁻¹ under rice-rice systems (RRS) in northeastern India that was affected by conservation tillage combined with fertilizer application [29].

Then, since the Gambier area was not cultivated from the beginning after being planted, the SOC sequestered in soil was accumulated. As suggested [30] that SOC accumulated would reach a peak in 5 to 10 y after a change in tillage method, while the new equilibrium was expected in 15 to 20 y (for change in tillage types) and 40-60 y (for crop rotation enhancement).

Table 1. Rate of OC sequestration at 0-30 cm depth under gambier cultivation

| Time Range          | Sequestration rate |
|---------------------|--------------------|
| 2-5 years old Gambier | 1.03               |
| 5-10 years old Gambier | 4.88               |

Some scientists explained that cover crops have a good potential to sequester OC on the agroforestry system. It was found that OC sequestration in soil planted with vine was higher under cover crop (Vicia faba) management than conventional tillage either in the sloping area (9.52 ± 0.34 g kg⁻¹) or in a flat area (10.47 ± 0.20 g kg⁻¹) [30]. Then they reported that SOC sequestration under conservation tillage management was 8.74 ± 0.20 g kg⁻¹ and 9.88 ± 0.11 g kg⁻¹, respectively, for sloping and flat area. Soil OC sequestration at the olive plantation was reported to be the highest rate (5.3 t C ha⁻¹ y⁻¹) under the organic amendment application [31]. Furthermore, the SOC sequestration rate in the temperate region was lower than that in the tropical region. The rate of OC sequestration was found to be 0.71 t ha⁻¹ y⁻¹ for mineral soils in temperate regions [32]. They also found that OC stock under uncultivated grassland was higher than that under abandoned fields.

3.3 Comparison of SOC Stock between Gambier and Forest Land Use
Compared to forest land use, the amount of SOC stock under Gambier was lower than that under forest land use. This finding agreed with the results found by Alidoust et al. [33] that land-use change from forest to other land use will reduce OC stock. Furthermore, they stated that the SOC stock on the top 30 soil in western Iran was found to be the highest in the forest compared to pasture, rain-fed, and irrigated farmlands. Then, the SOC stock under the Gambier cultivation area tended to increase by time, from 0.50 to 0.90 on the top 30 cm compared to that in the forest. The older the crops were, the more the OM accumulated in the soil under the Gambier cultivation.
As in forest, the OM yielded from the litter is just accumulated and then together with root exudates and senescent contributed to SOC on the top 30 cm soil. The contribution of litter on SOC stock was affected by the types and the age of the plant species [30]. As the crop became mature, the SOM storage under tea plantation in the sloping area increased [28]. Accelerated accumulation of OM between 5 and 10 years old Gambier was also due to the addition of the Gambier residue after being pressed to the soil. This addition is very important to keep the SOM above the critical value and to control erosion from the land since the Gambier was planted on the sloping area. As reported by scientists, the application of compost and N fertilizer to crop growth resulted in high SOC sequestration potential [15, 16].

3.4 Some soil physical properties and the relationship with SOC content

Based on Table 3, it was found that the soil in Lansano, both under Gambier cultivation and forest had fine texture classes (silty clay – clay). The OC content in soil was very low (<3%), it means that less SOC available as a binding agent for soil aggregate stability and for reducing soil weight per volume basis (BD). As a consequence, the soil became dense, high soil bulk density, and low soil hydraulic conductivity. The soil aggregates formed seemed to be mostly bound by the clay itself, which is easily degraded by water. Therefore, this soil becomes easily degraded when it is open and cultivated under a high annual rainfall area.

| Land Use         | SOC Gambier/SOC Forest |
|------------------|------------------------|
| Two years old Gambier | 0.50                  |
| Five years old Gambier | 0.54                  |
| Ten years old Gambier  | 0.90                  |
| Secondary Forest          | 1.00                  |

| Land Use  | OC (%) | BD (Mg m⁻³) | Aggregate Stab. Index | Hydraulic Cond.(cm h⁻¹) | Texture Class |
|-----------|--------|-------------|-----------------------|-------------------------|---------------|
|           | Mean   | SE          | Mean                  | Mean                    |               |
| Gambier-2 y | 0.90 ±0.12 | 1.27 ±0.55 | 0.34 ±0.01           | 1.08 ±0.56              | Silty Clay    |
| Gambier-5 y | 1.08 ±0.02 | 1.15 ±0.23 | 0.42 ±0.02           | 1.36 ±0.41              | Clay          |
| Gambier-10 y | 1.84 ±0.05 | 1.12 ±0.41 | 0.54 ±0.02           | 2.21 ±0.13              | Clay          |
| Forest    | 2.11 ±0.12 | 1.08 ±0.09 | 0.54 ±0.01           | 2.84 ±0.17              | Clay          |

The relationship between SOC and some soil physical properties is presented in Figure 2. As shown in Figure 2, it can be concluded that soil OC content significantly affected soil bulk density (R²=0.56). It was about 56% of the soil BD determined by the soil OC content. The correlation between SOC and soil BD was negative (r=-0.75). It means that increasing soil OC content would decrease the value of soil bulk density. This was found to be true since OC in the form of OM functions in creating and stabilizing soil aggregates, and the soil became more porous, the soil pore sizes created were in the balance between micro- and macro-aggregates. Macroaggregates resulted from OM binding agents were stable against water; therefore, they could pass water steadily. Organic matter could improve soil aggregation process, and the soil BD decreased by increasing SOM content in Ultisol [4]. Then, SOC was not yet significantly improved soil hydraulic conductivity and soil aggregate stability. However, there was a tendency of increasing soil hydraulic conductivity (R²=0.464, r=0.68).
and soil aggregate stability ($R^2=0.15$ or $r=0.39$) as the OC increased. It meant that the OC content of the soil determined 46% of soil hydraulic conductivity value. The higher the OC content was, the higher the rate of soil hydraulic conductivity ($r=0.68$); consequently, the less the chance of runoff causing erosion. Soil OC content tended to increase the soil aggregate stability, but in this case, it was not significantly ($R^2=0.15$ or $r=0.39$) affected yet. This insignificance could be due to the total content of SOC on the soil profile up to was still considered low. Therefore, the effect on aggregate formation and stabilization was very little.

Figure 3. Relationship between soil OC and some soil physical properties (BD, aggregate stability, and hydraulic conductivity) at Gambier and forest land use in Siguntur, West Sumatra.

It is expected that OC of the soil under Gambier crops in Lansano Siguntur increased by time to anticipate erosion that might happen due to high clay content and annual rainfall in the area. Returning Gambier residue after being pressed to the land is strongly recommended to keep the SOC stable in the soil.

4. Conclusion
SOC sequestration on the top 30 cm soil depth under Gambier cultivation in the sloping area was quite low. It started from 34.04, 37.13 to 61.53 Mg Ha$^{-1}$ for crops having 2, 5, and 10 years old, respectively. The rate of SOC sequestration at the first 5 years was 1.03 Mg Ha$^{-1}$ y$^{-1}$ and sharply increased for the period of the second five years (4.88 Mg Ha$^{-1}$ y$^{-1}$) of crop age. Soil OC under Gambier cultivation in the sloping area of the wet tropical region significantly decreased soil BD, increased soil hydraulic conductivity, and tended to increase the soil aggregate stability. It was suggested to regularly return the extracted leaves of the Gambier crops as an OM source to the soil in improving the soil's physical properties in anticipating environmental degradation and natural disaster.

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