Soil management practices in coffee-based agroforestry systems within Universitas Brawijaya Forest impact on maintaining soil carbon stock

S Kurniawan1*, P Hariyanto2 and R M Ishaq3
1Soil science department, Faculty of Agriculture, Universitas Brawijaya, Malang, Indonesia
2Agroecotechnology study program, Faculty of Agriculture, Universitas Brawijaya, Indonesia
3Research group of Tropical Agroforestry, Faculty of Agriculture, Universitas Brawijaya, Indonesia
*Corresponding author: syahrul.fp@ub.ac.id

Abstract. Farmer fertilization practices is one of effort on climate change mitigation and determine environmental services of agroforestry systems especially soil carbon stocks. The research aimed to assess soil carbon stock in smallholder agroforestry systems within Universitas Brawijaya (UB) Forest, East Java. The study was conducted on two different types of fertilizer application (e.g., organic, mixed organic and inorganic fertilizer) with three different doses of organic fertilizer (e.g., 5, 10, 15 kg tree−1) and 3 replications of each, totalling 18 plots. At each plot, soil sample was collected at fertilized and unfertilized areas with a depth 0-20 cm and 20-40 cm, then measured total organic C, soil bulk density, soil pH, and soil carbon stocks. Application of mixed fertilizer had 19-42 % lower of soil organic C as compared to those in application of organic fertilizer, resulted in decrease of soil carbon stock around 15-41 % at a depth 0-40 cm. In addition, the increases dose of organic fertilizer application up to 15 kg tree−1 decreased soil bulk density at 0-20 cm depth of soil around 8-10% as compared to dose 5 and 10 kg tree−1. Our study suggested to optimize fertilization practices for maintaining soil fertility and its relationship to coffee production.

1 Introduction
Soil plays an important role on global carbon cycle due to soil organic carbon (SOC) is a part of carbon cycle in the nature. In the form of CO2, carbon stock in the soil is around two or three times greater as compared to the atmosphere [1]. SOC is a crucial indicator for sustainable agriculture especially on maintaining soil quality such as soil bulk density, water availability, nutrient cycling, buffering and changes in soil pH, soil biodiversity, and sorption of soil pollutants [2 - 5]. Thus, maintaining SOC both quality and quantity is important to ensure sustainability of soil fertility and plant productivity [6 - 9].

Agroforestry systems is one of agricultural system that is contribute to maintain a large soil carbon stock. The role of agroforestry system in maintaining SOC both quality and quantity was through the shade of tree and soil management practices. Planting shade trees in agroforestry system over 10 years increased soil organic matter by 16–42 Mg ha−1 in the 0–45 cm layer [10]. While the role of soil management practices in agroforestry systems was showed by the previous study who reported that an increased in application of organic fertilizers was linearly increased in SOC levels through residue
accumulation [11, 12]. Another study was reported that long-term application of manure increased 0.10 Mg C ha\(^{-1}\) yr\(^{-1}\) [13]. The effect of fertilization on SOC was also shown by application of N fertilizer where nitrate fertilizer application resulted an increase in carbon sequestration [14].

Coffee-based agroforestry system is a common agroforestry system in Indonesia due to coffee is an important cash crop [15, 16]. In addition, coffee-based agroforestry systems are primarily held by smallholder farmers with an average holding of 1-2 hectares. One of coffee-based agroforestry systems areas in East Java – Indonesia is UB Forest, which is located in Malang Regency. UB Forest, with an area of 544 ha, is a Forest Area with a Special Purpose for Education (KHDTK) under managed by Universitas Brawijaya (UB) based on the mandate of the Minister of Forestry and Environment of the Republic of Indonesia since 2016. The existing conditions show that coffee-based agroforestry systems in Universitas Brawijaya (UB) forest covers more than half of the forest areas. In the UB Forest area, there are 2 groups of farmer settlements, namely Sumbersari and Sumberwangi where in each area are occupied by approximately 34 families (34 families) whose lives are very dependent on plants cultivated in the UB Forest area and forest areas belonging to Perhutani which are located in the top of UB Forest and plant cultivation in the yard [17]. Up to now, studies about the effect of soil management practices on soil carbon stock in coffee based agroforestry system within UB Forest are very limited. Therefore, it is important to assess the carbon stocks provided by agroforestry ecosystems under different soil management practices. The purpose of this study was to assess soil carbon stock in smallholder agroforestry systems within UB Forest, East Java. The results of this study may contribute to the improving on fertilizer application for the benefit of sustainability of soil fertility.

2 Methods

2.1 Study site characteristics
The study was conducted in the in Universitas Brawijaya (UB) Forest which is located at coordinates 7°49'300'' - 7°51'363'' S and 112°34'378'' - 112°36'526'' E, and administratively borders Batu City and Malang Regency. The UB Forest has elevation ranging from 900 – 1.300 m asl, with an average annual air temperature of 22 °C, and annual rainfall of 2004 mm/year during the period 2014-2018. The soil in the study area was derived from the parent material of volcanic material (i.e breccias, lava, tuff breccias, and tuffs) from the Arjuna-Welirang complex volcanoes [16], and generally classified as Inceptisol (USDA classification). Lava from mount Arjuno consisted of basalt olivin and andesit pyroksen, whereas mount Welirang resulted andesit augit hyperstein [18]. Topography in the UB Forest is dominantly 15 – 25%. Then, soil analysis was carried out in the Department of Soil, Faculty of Agriculture, Brawijaya University.

2.2 Research design
The research was designed on six farmer fertilization practices, including 3 different doses of organic fertilizer application (e.g 5 kg tree\(^{-1}\), 10 kg tree\(^{-1}\), and 15 kg tree\(^{-1}\)) and inorganic fertilization (e.g without inorganic fertilizer and with addition of inorganic fertilizer). Each fertilization practices has 3 replications, totally 18 research plots. The preliminary field survey was conducted to select representative plots in each fertilization practices, sized 60 m x 40 m, with the distance between observation plots was at least 50 m. Soil samples was collected at 2 distance from coffee stem (e.g. 0-50 cm and 50-100 cm) and 2 soil depths (e.g. 0-20 cm and 20-40 cm).

Based on preliminary interview, farmer is commonly manage an area of coffee agroforestry within UB Forest around less than 0.5 hectares until 2 hectares. The cultivated coffee plants are 4 to 12 years old with the percentage of age with the majority being 5-10 years old. The plant is planted under the pine as a shade tree. To increase the growth and production of coffee, farmers applied both organic and inorganic fertilizers. Coffee agroforestry farmer applied organic fertilizer (mainly chicken manure), or manure + inorganic fertilizers (Urea and NPK fertilizer). The doses of organic fertilizer applying by respondents can be classified in 3 groups, including 5 kg tree\(^{-1}\), 10 kg tree\(^{-1}\), and 15 kg tree\(^{-1}\). Whereas
the dose of inorganic fertilizer is 50-200 kg Urea ha\(^{-1}\), 100 – 300 kg NPK ha\(^{-1}\), and 50 – 400 kg Ammonium sulphate ha\(^{-1}\). The organic and inorganic fertilizer is applied once a year on November, but some farmers is occasionally applied inorganic fertilizer between March and April. Coffee production in UB forest is classified as low, dominantly ranging from 100 to 500 kg ha\(^{-1}\).

2.3 Soil samples collection
Soil sampling was carried out in 18 observation plots between February and March 2021. In each study plot (size 60 m x 40 m), 5 representative subplots of 5 m x 5 m were randomly determined (Figure 1). Soil samples were taken in each sub plot at 2 distances from the coffee stem (0-50 cm and 50-100 cm) and soil depth intervals namely 0-20 cm and 20-40 cm using a soil auger. Soil samples that have been taken were placed into plastic bags and coded according to fertilization types, fertilizer dose, distance from coffee stem, and depth of soil. Then, the soil sample transported to the Department of Soil, Faculty of Agriculture – Universitas Brawijaya to be air-dried for ± 7 days, and mashed until it passes a 2 mm sieve.

A soil sample from each sub plot within replicate plots that has been air dried and passed through a 0.05 mm sieve was weighed (about 20 grams) and was composited for measurement of soil organic carbon. A sampling of soil bulk density was carried out in each representative plot at 2 depths of the soil using soil core and given a location code.

![Figure 1](image1.png)

Figure 1. Soil sampling design at 5 sub plot in each plot (A) and at 2 distances from coffee stem (0-50 cm and 50-100 cm) with 2 different soil depth (0-20 cm and 20-40 cm) for each sub-plot (B).

2.4 Laboratory analysis and calculation of soil nutrient stocks
Air-dried soil samples that passed through 2 mm sieved were used for measuring of soil organic C [19]. Soil bulk density was measured using the soil core. The soil nutrient stocks expressed in g m\(^{-2}\) or kg m\(^{-2}\) was obtained from the following calculation [20]:

\[
\text{Soil nutrient stocks (g m}^{-2}\text{)} = \frac{Ec (g kg}^{-1}\text{)} \times BD (g cm}^{-3}\text{)} \times \Delta D (cm) \times 10000 cm^2 cm}^{-3}\text{)} \times 1000 g kg}^{-1}\text{)}
\]

(1)

Note: Ec = soil nutrient concentration, BD = bulk density (the value was used from forest area), and \(\Delta D\) = soil depth. Then, the soil nutrient stocks (g m\(^{-2}\)) was converted to kg m\(^{-2}\) as a final unit.

2.5 Statistical analysis
Statistical analysis was carried out to determine the effect of differences in organic fertilizer doses and its combination with inorganic fertilizer on soil organic C at each soil depth (0-20 cm and 20-40 cm). The normality test was performed using the Shapiro Wilk’s test for all parameters. Data analysis was performed using the Linear Mixed Effects (LME) model to determine the effect: 1) fertilization types with all fertilizer dose, and 2) fertilizer dose at each fertilization, where each factor was compared as a fixed factor and a random factor included distance from coffee stem and replication [21]. Fisher's least significant difference (LSD) test was used at the 5% level to find significant differences among 2
fertilization types and 3 organic fertilizer doses. The difference was considered statistically significant if $P \leq 0.05$. The study also considered marginal significance at $p \leq 0.09$ due to the research design comprised the inherent spatial variability in filed research. Pearson correlation analysis was conducted to evaluate the relationships between SOC and other soil characteristics (i.e., soil bulk density and soil pH). All statistical analyzes were carried out using R statistical program.

3 Results and discussion

3.1 Effect of fertilization types on soil organic carbon and soil carbon stocks

Farmer fertilization practices in coffee based agroforestry system within UB forest was significantly ($P = 0.012$) affected to soil organic carbon (SOC). This was supported by 16% higher of SOC in the depth 0-20 cm ($5.15 \pm 0.20$ g 100 g$^{-1}$) as compared to those in the depth of 20-40 cm ($4.45 \pm 0.18$ g 100 g$^{-1}$).

Application of organic fertilizer combined to inorganic fertilizer decreased 19 % to 42 % of SOC both in the top and bottom soils (0-20 cm and 20-40 cm depth of soil) as compared to applying organic fertilizer without inorganic fertlizer (Figure 2A-D). As consequence, soil C stock in the coffee agroforestry system with application organic fertilizer combined to inorganic fertilizer was 15 to 41 % lower as compared to those in the plot with only applying organic fertilizer. This was probably due to application of inorganic fertilizer was expected to increase soil microbial activities on the rate of organic matter decomposition, resulted decreased in soil organic C and soil C stock. The previous study conducted in tropical rainforest stated that inorganic fertilization increased soil organic matter decomposition [22]. Our finding was also in line with the statement from previous study Averill and Waring [23] that experimental N addition increased the rates of soil organic matter decomposition, resulting decreases in soil C stock. Another study also reported that the increases in N fertilization facilitated soil C stock through increases root biomass production and decreased SOM decomposition in the rhizosphere due to reduced N limitation [24].

Further, application of inorganic fertilizer combined to organic fertilizer accelerated to decrease soil pH. This was supported by the lower soil pH in the coffee agroforestry system with the application of organic fertilizer combined to inorganic fertilizer ($5.06 \pm 0.09$ and $5.30 \pm 0.05$) as compared to those with the application organic fertilizer without inorganic fertilizer ($5.37 \pm 0.04$ and $5.43 \pm 0.03$). The addition of N through inorganic fertilizer (urea, ammonium sulphate, or NPK) lead to increase nitrification process ($\text{NH}_4^+$ converted to $\text{NO}_3^-$) and release hydrogen in the soil solution. As consequence, the soil pH ($\text{pH H}_2\text{O}$) will decrease, a well-known soil acidification. Our finding in line with the meta analysis of the effect of N addition on soil microbes in terrestrial ecosystems [25] who reported that the addition of N increased N availability in the soil and resulted in soil acidification. The strongly positive correlation between SOC and soil pH both in the 0-20 cm ($r = 0.49$, $P = 0.002$) and in the 20-40 cm ($r = 0.58$, $P = < 0.01$) depth of soil indicated the low effect of organic acid from decomposition of organic fertilizer on soil acidification. Furthermore, although the study detected un-significant differences ($P \geq 0.05$) of soil bulk density among fertilization types, the strong negatively correlated between SOC and soil bulk density ($r = - 0.55 - -0.62$, $P = < 0.01$) indicated the increased in SOC decreased soil compaction.

Coffee based agroforestry systems within UB Forest stored a large C stock, including 9.49 – 10.87 kg C m$^{-2}$ in the depth 0-20 cm and 6.63 – 9.37 kg C m$^{-2}$ in the depth 20-40 cm. This C stock was relatively comparable to the measurement on 2017 which was reported that pine + coffee systems in UB Forest stored 21.7 – 23.3 kg C m$^{-2}$ at top 50 cm depth of soil [17]. The high soil C stock in the coffee based agroforestry systems within UB Forest showed that differences in fertilization practices by farmer is consistent in maintaining the sustainability of C stock. However, the trend that addition of inorganic fertilizer (i.e. N and P) decreased soil C stock and soil pH needs attention in future to control the concentration of N and P addition not only for increasing coffee production, but also for minimizing soil acidification and maintaining soil organic matter.
Figure 2. Soil organic C (A) and soil C stock (B) at 0-20 cm depth, soil organic C (C) and soil C stock (D) at 20-40 cm depth from two fertilization types (e.g. Mixed of organic and inorganic, and organic fertilizers only) at coffee based agroforestry systems within UB Forest.

3.2 Impacts of fertilizer doses on soil organic C and soil C stock
Evaluation of the impact of fertilizer doses on soil organic C and soil C stock was conducted in each farmer fertilization types. In the plot where farmer is only applied organic fertilizer, differences in organic fertilizer doses did not significantly affected to soil organic C and soil C stock at 0-20 cm and 20-40 cm depth of soil (Figure 3A-C). However, soil C stock at 20-40 cm depth of soil (Fig. 3D) in coffee agroforestry with application of 15 kg organic fertilizer tree\(^{-1}\) had higher soil C stock (9.42 ± 0.10 kg C m\(^{-2}\)) as compared to application 5 kg organic fertilizer tree\(^{-1}\) (8.76 ± 0.33 kg C m\(^{-2}\)). This was showed that the higher dose addition of organic fertilizer had a larger soil C stock than the lower dose of organic fertilizer application. Since the type organic fertilizer applied by farmer is similar, the study found that the quantity of organic material added to soils are the major factors in controlling soil C stock probably through their role on affecting soil microbial groups and the activity of microorganisms involved in nutrient cycling. The previous research showed that microbial biomass C increased up to 100%, more by high rates and composted than by low rates and fresh paper mill residuals [26].
By combining with inorganic fertilizer, the increases in application dose of organic fertilizer (10 and 15 kg tree\(^{-1}\)) resulted 17-38\% higher of soil organic C and soil C stock as compared to the application dose of 5 kg organic fertilizer tree\(^{-1}\) at 0-20 cm depth of soil (Figure 4A-B). At the depth of 20-40 cm, the study was also detected 23-29\% higher soil organic C with application dose of 10 kg organic fertilizer tree\(^{-1}\) and 15 kg organic fertilizer tree\(^{-1}\) than application 5 kg organic fertilizer tree\(^{-1}\) (Figure 4C). However, soil C stock at 20-40 cm depth of soil was comparable among different application doses of organic fertilizer combined to inorganic fertilizer (Figure 4D).
Figure 4. Soil organic C (A) and soil C stock (B) at 0-20 cm depth, soil organic C (C) and soil C stock (D) at 20-40 cm depth from different application doses of organic fertilizer (e.g. 5, 10, 15 kg tree⁻¹) combined to inorganic fertilizer at coffee based agroforestry systems within UB Forest.

4 Conclusion
Soil management practices especially fertilization practices by farmer in coffee agroforestry systems within UB Forest contributed to maintain soil organic C. Application of organic fertilizer resulted 19-42 % higher of soil organic C as compared to application of organic fertilizer combined to inorganic fertilizer. In addition, the increases application doses of organic fertilizer resulted in increase soil C stock approximately 0.66 kg C m⁻² at 20-40 cm depth of soil. Furthermore, the increases application dose of organic fertilizer (combined to inorganic fertilizer) was also increased 23-29% higher soil organic C at the depth of 0-20 cm. Therefore, optimizing fertilizer practices by farmer is not only to maintain the sustainability of coffee production, but also environmental services of coffee agroforestry systems within UB Forest especially on regulating carbon stocks.

Acknowledgements
The study was implemented and partly funded by PNBP research fund of Agriculture faculty Universitas Brawijaya 2021 and Centre for Ecology and Hydrology (CEH), UK through Sustainable Use of Natural Resources to Improve Human Health and Support Economic Development (SUNRISE) Project. The author thanks to UB Forest management board and the farmer for the permission to collect soil samples,
Sri Padmi Wulandari and Wahyu Indrayanto for soil laboratory analysis, Naysila and Ifa for the fieldwork.

References

[1] Post W M and Kwon K C 2000 *Global Change Biology* 6 317-327
[2] Verma B C, Datta S P, Rattan R K and Singh A K 2013 *J. Environmen. Biol.* 34 1069-1075
[3] Wang X, Butterly C R, Baldock J A and Tang C 2017 *Sci Total Environ.* 587 502-509
[4] Wang Z, Liu S, Huang C, Liu Y and Bu Z 2017 *Catena* 152 1-8
[5] Qi F, Kuppusamy S, Naidu R, Bolan NS, Ok Y S, Lamb D, Li Y, Yu L, Semple K T and Wang H 2017 *Crit. Rev. Environ. Sci. Technol.* 47 795-876
[6] Ramesh T, Bolan N S, Kirkham M B, Wijesekara H, Kanchikerimath M, Rao C S, Sandeep S, Rinklebe J, Ok Y S, Choudhury B U, Wang H, Tang C, Wang X, Song Z and Freeman O W 2013 *Advances in Agronomy* 156 1-107
[7] Tisdale S L, Nelson W L, Beaton J D and Havlin J L 1995 *Soil Fertility and Fertilizers* (New York: Macmillan Publ. Co)
[8] Qin S, Hu C, He X, Dong W, Cui J and Wang Y 2010 *Appl. Soil Ecol.* 45(3) 152-159
[9] Zhao Y G, Liu X F, Wang Z L and Zhao S W 2015 *Catena* 133 303-308
[10] Beer J, Muschler R, Kass D and Somarriba E 1998 *Agrofor Syst* 38 139-164
[11] Singh B B and Lal R 2005 *Environ. Dev. Sustain.* 7 161-184
[12] Kong W D, Zhu Y G, Fu B J, Marschner P, He J Z 2006 *Environ. Pollut.* 143 129-137
[13] Buyssse P, Roisin C and Aubinet M 2013 *Agric. Ecosyst. Environ.* 167 52-59
[14] Alvarez R 2005 *Soil Use Management* 21 38-52
[15] Lewin B, Giovannucci D and Varangis P 2004 *Agriculture and Rural Development Discussion* (Washington: The World Bank)
[16] Left B, Ramankutty N and Foley J A 2004 *Global Biochem. Cycles* 18 1-27
[17] Kurniawan S, Utami S R, Mukharomah M, Navarette I A and Prasetya B 2019 *AGRIVITA Journal of Agricultural Science* 41 416-427
[18] Badan Geologi 2014 *Gunung Arjuna – Welirang* (Bandung: Pusat Vulkanologi dan Mitigasi Bencana Geologi)
[19] Walkley A and Black IA 1934 *Soil Sci* 37 29-38
[20] Allen K, Corre M D, Kurniawan S, Utami S R, and Veldkamp E 2016 *Geoderma* 284 42–50
[21] Crawley M J 2009 *The R book* (Chichester: John Wiley and Sons Limited)
[22] Cleveland C C and Townsend A R 2006 *PNAS* 103(27) 10316-10321
[23] Averyll C and Waring B 2017 *Global Change Biology* 24 1417-1427
[24] Zhang H, Wang J and Kuyzakov Y 2016 *Applied Soil Ecology* 108 47-53
[25] Zhou D, Wang C, Zheng M, Jiang L and Luo Y 2017 *Soil Biology and Biochemistry* 115 433-441
[26] Leon M C C, Stone A and Dick R P 2006 *Appl. Soil Ecol.* 31 199-210