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Assessment of Carbon Stock and Greenhouse Gas Emissions of Selected Coffee-Based Agroforestry Farms in Timor Leste

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Abstract

Agroforestry is an important carbon sequestration strategy because of carbon storage potential in its multiple plant species and soil as well as its applicability in agricultural lands and in reforestation. The study was conducted in selected coffee-based agroforestry farms in Gleno, Ermera District, Timor Leste to determine the amount of carbon stocks and greenhouse gas emissions in the management of coffee-based agroforestry farms. Results reveal that agroforestry coffee cropping pattern had a carbon stock composed of 6.425 Mg ha^{-1} biomass, 2.01 Mg ha^{-1} necromass, and 157.17 Mg ha^{-1} soil organic carbon. For the carbon stock stored in the monoculture coffee cropping pattern, a biomass of 5.321 Mg ha^{-1}, necromass of 1.32 Mg ha^{-1}, and soil organic carbon of 128.74. Mg ha^{-1} were recorded while for the pruned coffee cropping pattern, biomass of 2.771 Mg ha^{-1}, necromass of 1.82 Mg ha^{-1}, and soil organic carbon of 69.29 Mg ha^{-1} were found. Moreover, the greenhouse gas emission CO_2 absorbed by coffee plants across cropping patterns were the following: agroforestry coffee, 24.156 t/ha^{-1}, monoculture coffee, 19.520 t/ha^{-1} and pruned coffee, 10.177 t/ha^{-1}. Abovementioned results reveal that coffee-based agroforestry system a coffee-based agroforestry is considered as an effective solution in combatting heightened atmospheric GHGs concentration and climate change while at the same time addressing concerns on socio-economic stability.

Keyword: Carbon stock; Agroforestry Coffee; Gas Emission.

1. Introduction

Timor Leste became an independent nation on May 20, 2002. One of its foremost challenges is its dwindling natural resources. This situation reflects the whole of Southeast Asia because its forest resources have been degraded during the past years and decades [11]. One of the most valued commodities of Timor Leste is coffee. Coffee producers in the country use a variety of agricultural techniques, including shaded and unshaded monoculture, agroforestry, and traditional polyculture with organic and conventional practices to meet the increasing demand of coffee in the world market.

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Moreso, coffee-based agroforestry is considered as an effective solution in combatting heightened atmospheric GHGs concentration and climate change while at the same time addressing concerns on socio-economic stability [6,7].

Climate is the outcome of the interactions between the atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere – the highly complex climate system. The climate system is influenced by its own internal dynamics, external forcings (e.g., volcanic eruptions, solar variations) and anthropogenic forcings (e.g., changing composition of the atmosphere and land use change). Moreover, climate is determined by measuring the different meteorological variables such as temperature, humidity, atmospheric pressure, wind, precipitation, and other meteorological variables were measured for a long period of time for determination of climate [2]. It is the statistical description in terms of the mean and variability of relevant quantities over a period ranging from months to thousands or millions of years [5].

2. Methodology

2.1. Place and time of study

The research was conducted in the municipality of Gleno Ermera, specifically in Gleno Fatukeru and Ermera districts, Geographically, Gleno sub-district is located at (S 080 42’ 36, 5” E 1250 26’ 23.3”), (S 00045’ 22.2” E 1250 25’ 30.7”), and (S 080 42’ 49, 4” E 1250 26’ 47, 3”). The research site was selected based on the following criteria: (1) with farmers who were directly involved as coffee farming and (2) with a rural population consisting mostly of coffee farmers. These areas are located in the western region of Timor Leste.

2.2. Equipment used was:

1. GPS for determining the coordinate of the observation plots
2. Plastic rope for marking the observation plots
3. Phiband for measuring tree diameter
4. Soil ring samplers for collecting soil samples
5. Meter tape for measuring the observation plot
6. Woody quadrant with a size of 0.5 m x 0.5 m for marking the spots of colleting biomass and necromass of undergrowth/shrubs

7. Knife/scissors for collecting biomass samples from undergrowth

8. Plastic label for labeling each sample

9. Electric oven for drying biomass samples

10. Scale for weighing object samples

11. Tally sheet for recording observation data in the field

12. Calculator and computer for processing data and preparing reports

13. Stationery for recording Data

14. Laboratory equipment for analyzing carbon contents of samples.

2.3. Study Procedures

In this study, data collection focused on rural coffee farm households in the chosen study areas. Random sampling was used in selecting the sample respondents. Primary data collection was conducted in two ways: (1) individual survey with the 85 respondents from Ermera municipality; and (2) key informant interviews (KIIs) with the village chiefs and the Municipal Agricultural Officers. Secondary data were gathered from various sources, including the Office of the Ministry of Agriculture and Fisheries (MAF). Statistics of Timor Leste were accessed from online sites. The nested plot sampling method (NPSM) [3] was used to identify and obtain biomass measurements of coffee trees, herbaceous crops like understorey vegetation (shrubs and grasses) present within the sampling frame that was set up per plot identified the management of the agroforestry farms within the three Gleno Ermera district sites.

In this study, carbon content of various coffee tree biomass was assumed to be 46% as proposed by [3]. Commonly used allometric equations in previous studies were used as bases for carbon stock and coffee plant parameters. For GHG emission equivalent calculations, crop production inputs were converted kg CO_2e for GHG emissions. GHG intensity calculated as the ratio of GHG emissions to the output of energy for each crop (in kilograms of carbon dioxide equivalents per megajoule of biomass energy output [1].

3. Results and Discussion

3.1. Carbon Stock in Aboveground Biomass (AGB) in Three Cropping Patterns

Estimation of the aboveground carbon stocks was carried out by measuring the components of carbon stock in three types of coffee cropping patterns which are the pruned coffee, monoculture, and agroforestry coffee. Carbon content was measured in three components across patterns such as biomass, understorey, and litter. In each cropping pattern, three observation (sites) plots were made from which three carbon stock components were [3]. The largest total carbon stock above the surface of 6.582 (Mg ha^{-1}) was observed in plots with agroforestry cropping pattern followed by the monoculture cropping pattern with 5.319 (Mg ha^{-1}) and the smallest amount was recorded in the pruned coffee system with 2.773 (Mg ha^{-1}). From these three cropping systems, the agroforestry coffee cropping pattern has the largest carbon stock which could be attributed to the more intensive treatment where land use is highly optimized.

This greatly affects the growth of coffee plants as the main crop. For example, applying fertilizers to secondary crops in this system also affects the growth of the main tree, which is coffee, thus affecting the biomass of the coffee tree itself which makes the amount of carbon stock in the coffee plant in the agroforestry cropping pattern greater than the other two cropping patterns.

This in turn makes the carbon stock in the coffee agroforestry cropping pattern the largest. Results of the measurements made are shown in Table 1.

Table 1: Composition of the carbon stock above the surface in three cropping patterns.

Cropping pattern	**Composition**		**Carbon Stock Mg ha^{-1}**
Agroforestry Coffee	Biomass	Tree	6.425
		Understorey	0.63
	Necromass	Litter	2.01
	Total		6.582
Monoculture Coffee	Biomass	Tree	5.321
		Understorey	0.67
	Necromass	Litter	1.32
	Total		5.319
Pruned Coffee	Biomass	Tree	2.771
		Understorey	0.57
	Necromass	Litter	1.82
	Total		2.773

Source: Primary data processed, 2020.

Tree biomass. The largest percentage of carbon stocks are in tree biomass, which are the coffee plants themselves. The percentage distribution of the composition of carbon stocks from pruned coffee planting pattern are as follows: 50% tree biomass, 35% understorey biomass and 15% from litter. For the monoculture coffee, the percentage of carbon stocks are: 56% in tree biomass, 29% in understorey biomass and 15% in litter. In the agroforestry coffee, percentage of carbon stocks are: 58% in tree biomass, 32% in understorey biomass and 10% from litter (Table 2).

Table 2: Percentage distribution of carbon stock composition of three different coffee-based cropping patterns.

Carbon stock composition	Cropping pattern		
	Agroforestry coffee	Monoculture coffee	Pruned coffee (%)

	(%)	(%)	
Tree biomass	58	56	50
Understorey	32	29	35
Necromass	10	15	15

Source: Primary data

This shows that coffee as the main crop stores the largest carbon stocks out of the three coffee-based cropping patterns. Coffee plants have large tree biomass because they are woody while the understoery and litter components are only in the form of lighter biomass thus smaller carbon content.

Understorey. The carbon content in understorey biomass for the three coffee cropping patterns was not too different. For pruned coffee, 0.57 Mg ha^{-1} was recorded; for monoculture coffee, 0.67 Mg ha^{-1} while for agroforestry coffee, 0.63 Mg $ha^{-1.}$ The biomass of understorey is relatively very small since coffee plant as a main crop has a dense branching character such that the amount of sunlight that can penetrate to the surface of the soil is limited to allow the growth of understory species. The fairly dense branches of coffee plants block the penetration of sunlight to the floor or soil surface which affect the small carbon stock from the understorey biomass.

Necromass. Total carbon stocks originating from necromass did not differ too much in the three cropping patterns. Pruned coffee had a 1.82 $Mgha^{-1}$ necromass, monoculture coffee recorded 1.32 Mg ha^{-1} while the agroforestry coffee had 2.01 Mg ha^{-1}. From these recorded data, the agroforestry coffee cropping pattern had largest necromass carbon stock among the other cropping patterns observed. This could be attributed to the seasonal planting of agroforestry cropping pattern where the litter from these annual crops supports the amount of carbon stock from necromass. The other two cropping patterns (i.e., pruned and monoculture) have no seasonal crops resulting to relatively smaller carbon stock in its necromass.

Differences in biomass in each cropping pattern can be caused by the differences in plant structure, constituent components, and tree population densities on a land (Mutuo and colleagues 2004). The constituent components of the agroforestry cropping pattern has the highest carbon content value due to the availability of seasonal crops and staple plants compared to carbon content of the other two cropping patterns. Besides, the intensive maintenance of agroforestry cropping patterns has a major effect on plant biomass. In addition, the density in coffee plantations with higher agroforestry cropping pattern has the same condition. This is supported by the findings of Subekti Rahayu and colleagues (2003) who found that a land use system consisting of trees species with high wood density values have higher biomass compared to land that has tree species with low wood density values. Moreover, [11]. stressed that agroforestry systems in general, can maintain the physical properties of the topsoil as in forest systems. Agroforestry systems can maintain soil physical properties through the production of litter that can increase organic matter, increase soil and root biology activities, and maintain and increaser the availability of water in the root layer.

Agroforestry systems can maintain the physical properties of the topsoil that is needed to support the plant growth. The relatively dense canopy of plants and trees throughout the year causes most of the rainwater to fall indirectly to the soil surface and keeps the soil protected from water blows that can break and crush aggregates into particles that are easily washed away by water flow. It also maintains soil organic matter content in the top layer through weathering of litter that falls to the soil surface throughout the year. The regular trimming of the canopy trees which are added to the soil surface can also increase the soil organic matter content. Such conditions can improve the soil structure and porosity, and can further increase the infiltration rate and water holding capacity.

Agroforestry systems generally have a canopy that covers some or all of the land surface and some will decompose gradually. The presence of litter covering the soil surface and the canopy of trees causes the conditions at the soil surface and soil layer to be more humid and lowers the temperature and light intensity. Such microclimatic conditions are very suitable for the reproduction and activity of organisms. The activities and development of these organisms accelerate due to the availability of organic material as an energy source. The activities of macro and microorganisms affect several physical properties of the soil, such as the formation of macropores (bio pores) and the consolidation of aggregates. The increase in number of macropores and stability of aggregates in turn increase the infiltration capacity and aeration properties of the soil. Trees are the largest component of aboveground biomass. Carbon stocks in a land use system are influenced by the type of vegetation. A land use system consisting of trees with species that have a high value of wood density values will also have higher biomass when compared to a land system that has species with low wood density values. Vegetation that grows above the soil surface has the ability to bind carbon dioxide from the atmosphere through photosynthesis, this will affect the amount of the carbon stock of the existing trees in a land. The higher the density of the tree wood planted, the more carbon is stored in tree biomass.

3.2. Carbon Stocks in Soil

Measurement of carbon below the surface of the soil is done by first taking a soil sample and testing it in the laboratory to determine the fresh weight (Fw) and the dry weight (Dw) of soil samples and organic C content (% C). In this study, the carbon stock below the soil surface is calculated only at the depth of 15 cm which is the limit for sampling from the topsoil layer.

There is also a large amount of carbon stock below the soil surface in the three coffee-based cropping patterns. Results reveal that the carbon stock below the soil surface in the agroforestry coffee cropping pattern was 157.17 Mg ha^{-1} . This is the largest carbon stock compared to the monoculture coffee cropping pattern with 128.74 Mg ha^{-1} and pruned coffee cropping pattern with only 69.29 Mg ha^{-1} (Table 3). The organic carbon in agroforestry coffee cropping pattern is very high due to an intensive soil processing system as well as the addition of nutrients through the maintenance of seasonal crops which makes litter break down quickly and becomes the cause of a large amount of organic carbon in the soil. This also has been proven in the carbon stock at the necromass content where the agroforestry coffee cropping pattern has the greatest value compared to the other two cropping patterns.

Table 3: Belowground carbon stock in three different coffee-based cropping patterns.

Amount of sample	Below ground carbon stock (Mg ha^{-1})		
	Agroforestry Coffee	Monoculture Coffee	Pruned Coffee

1	129.36	147.47	66.88
2	184.97	110.02	71.71
Total	314.33	257.49	138.59
Average	157.17	128.74	69.29

The conditions are quite different for the pruned coffee cropping pattern where it has the smallest carbon stock below the soil surface. This is directly proportional to the conditions in the field where in this cropping pattern the soil is more open and that a greater percentage of sunlight goes through the soil surface which resulted in less soil decomposition activity compared to the other two cropping patterns.

In agroforestry coffee cropping pattern, soil moisture was higher and that the pruning maintenance activity causes the fall of leaf litter on the floor which makes the decomposition material lesser. In this study, observation of carbon stocks below the soil surface is limited to a depth up to 15 cm because at this layer the topsoil is still dominant and the distribution is evenly distributed on the land. This is in agreement with [8]who have stated that the level of organic content decrease along with the increase of soil depth because organic matter is only applied or falls on the ground. Thus, the organic material accumulates in the topsoil layer and partially washed into the deeper layer (subsoil). Most of the organic matter at this location is the result of the decomposition of the litter above it and the treatment of plant maintenance in the form of fertilization (in this case, chemical fertilizers).

3.3. Total Carbon Stock

Based on the results of the study, the largest carbon stock from the three coffee-based cropping patterns is found in the coffee agroforestry planting pattern. The total carbon stock of agroforestry coffee cropping pattern was obtained from the biomass, necromass, and belowground. The agroforestry cropping pattern has the largest carbon stock value compared to other two cropping patterns. Results reveal that increasing the effectiveness of land use by planting staple crops (in this case, coffee) combined with seasonal crops can increase the yield/value of the crop. Other than increase in yield, agroforestry cropping pattern has general environmental benefits through an increase of high levels of carbon stock (Fig. 1).

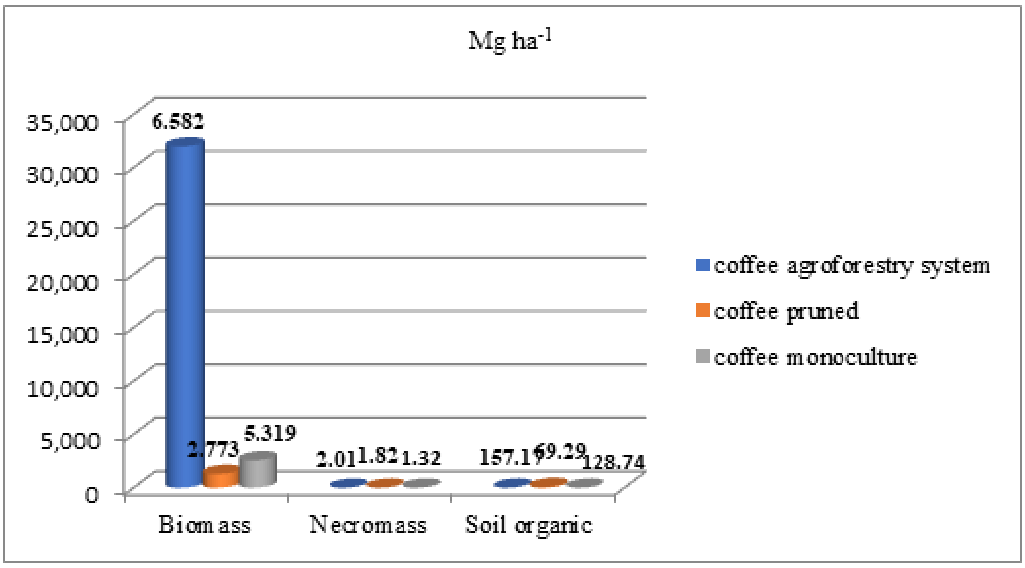

Figure 1: Total carbon stock from three coffee-based cropping patterns.

Moreover, total carbon stock of three coffee-based cropping patterns were computed and compared using commonly used allometric equations. Computed aboveground biomass shows that the agroforestry coffee recorded the highest aboveground biomass (6.425 Mg C ha^{-1}) and litter biomass (2.01 Mg C ha^{-1}). On the other hand, monoculture coffee placed second in aboveground biomass (5.321 Mg C ha^{-1}) followed by pruned coffee (2.773 Mg C ha^{-1}). Monoculture had higher floor litter biomass than the other two cropping patterns. Agroforestry coffee has the greatest total carbon yield on biomass (CY) with 6.425 Mg C ha^{-1} and total soil organic carbon (SOC) with 157.17 Mg C ha^{-1} compared to the other two cropping patterns. In a similar manner, total C stock and total CO_2 stock, agroforestry recorded the highest values. Meanwhile, in terms of net C emission, agroforestry coffee had the lowest (5.959 C_{2e} Mg ha^{-1}) and monoculture coffee with the highest (27.737 C_{2e} Mg ha^{-1}). Pruned coffee obtained the lowest net C stock (2.773 C Mg ha^{-1}) and agroforestry coffee with the highest (6.425 C Mg ha^{-1}). Mono-coffee had the lowest net CO_2 sequestration of -22.418 Mg C ha^{-1} followed by pruned coffee with -16.829 Mg C ha^{-1} and agroforestry coffee with 0.623 Mg C ha^{-1}. Details are shown in Table 3.

Previous studies reveal that coffee arabica carbon stocks were lower than that of Acacia sp. stands (155.97 Mg ha^{-1}), cempedak (*Artocarpus integer*) trees (196.61 Mg ha^{-1}), durian (*Durio zibethinus*) trees (134.11 Mg ha^{-1}), and langsat (*Lansium domesticum*) trees (109.08 Mg ha^{-1}) Yet, there was no information about the ages of the Acacia, cempedak, durian, and langsat trees. In addition, carbon content of the coffee arabica with agroforestry multistrata type recorded 0.9 to 1.86 Mg ha^{-1}, simple agroforestry, 0.6 to 0.97 Mg ha^{-1} and monoculture, 0.5) Mg ha^{-1}.

Overall, results of the study support the hypothesis that coffee-based agroforestry cropping pattern increases the capability in carbon sequestration compared to monoculture and pruned cropping patterns.

3.4. Greenhouse Gas Emission

The vast majority of greenhouse gas emission is often represented in terms of carbon dioxide. In the present study, GHG emission is explained through carbon dioxide absorbed by coffee plants. Coffee farming is responsible for emitting GHG gases caused by primary and agricultural activities. The use of chemicals, fertilizers, and other machineries/equipment can directly and indirectly produce emissions. Greenhouse gas emissions as a result of the activities inside the coffee plantation production system include carbon dioxide, nitrous oxide, and methane compounds. On the other hand, coffee production has its share in GHG emission especially when other trees are planted alongside coffee plants. The integration of trees in the production systems reduces the climate impact of coffee production (https://ccafs.cgiar.org/news/keys-climate-friendly-coffee-production).

3.5. Carbon Dioxide Absorbed by Coffee Plant

The potential of CO_2 gas absorption within the coffee plant was measured using the comparison of the formula between relative molecular mass of CO_2 gas and a mass of elements C (Rm CO_2: Ra C) = 44/12 or 3.67, which was used as a continuing value then multiplied by the amount of carbon content. Computed CO_2 absorbed by coffee plants across cropping patterns are the following: agroforestry coffee, 24.156 Mg ha^{-1}, monoculture coffee, 19.520 Mg ha^{-1} and pruned coffee 10.177 Mg ha^{-1} (Fig. 2). The CO_2 gas absorption increased with the corresponding increase in age of coffee plants. Results of the study are in agreement with [9] who reported that recent studies under various agroforestry systems in diverse ecological conditions showed that tree-based agricultural systems stored more C in deeper soil layers near the tree than away from the tree compared to treeless systems. Higher soil organic carbon content was associated with higher species richness and tree density. The extent of C sequestered in AFSs depends to a great extent on environmental conditions and system management.

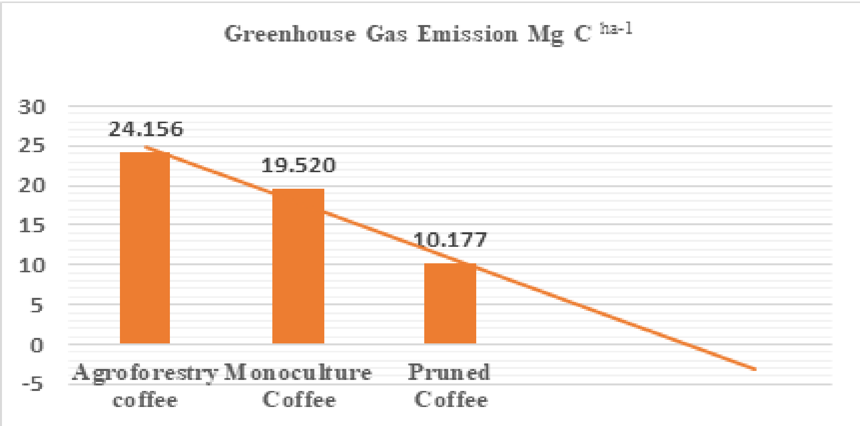

Figure 2: Computed CO_2 absorbed by coffee plants across cropping patterns.

4. Conclusions and Recommendations

Results of the study suggest that the coffee-based agroforestry system is an ideal approach in coffee production. With coffee as, the main plant and combining it with other cash crops in the same piece of land could become not only a source of additional income to small farmers but also help conserve soil, water, nutrients and microorganisms. Agroforestry system in coffee plantation could play an important role in environmental protection by mitigating GHG emission. Furthermore, the results of the study suggest that coffee-based agroforestry cropping system in selected research sites has high capability in carbon sequestration and in reducing greenhouse gas emissions compared to other cropping patterns considered. Therefore, coffee-based agroforestry cropping system was able to show a promising role in response to soil conservation, land degradation and bridge the gaps between climate change and mitigation strategies. Based on these findings, the following are suggested: (1) Promote agroforestry coffee cropping pattern to serve as an alternative system of reducing and mitigating carbon dioxide from the atmosphere through carbon sequestration. (2) Encourage traditional smallholder coffee farmers to practice agroforestry in order to improve their income through the integration of other crops in their coffee farms and help in addressing the problem of soil degradation. (3) Incorporate other cash crops as well as perennial woody species in coffee plantation because it can contribute to C storage in vegetation and increase soil C through litter fall and root exudates. (4) Conduct training with emphasis on the benefits of agroforestry for coffee farmers in coordination with the village chief. Through this training, improved technologies will be shared to coffee farmers for better farming management practices. (5) Further studies on the dynamics of carbon stock and greenhouse gas emission in other crop-based systems should be pursued to validate results of this research.

Acknowledgements

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Appendices

Table 3: Total carbon stock from three coffee-based cropping patterns.

Type of Coffee-Based Cropping System	Carbon Yield on Biomass Mg C ha^{-1}				CY on Biomass		SOC		Total		Net C Emission	Net C Stocks	Net Co_2 Sequestrations
	Aboveground Biomass				Total	%	Total	%	C Stocks	CO_2 Stocks	$MgCO_{2e}$ ha^{-1}	$MgCO_{2e}$ ha^{-1}	$MgCO_{2e}$ $^{ha-1}$
	UPS	UDS	FLB	WN	Mg C ha^{-1}		Mg C ha^{-1}		Mg C ha^{-1}	Mg CO_{2e} ha^{-1}			
Agroforestry coffee	6.423	0.63	2.01	-	6.425	44	157.17	44	6.582	24.156	5.959	6.582	0.623
Mono-coffee	5.319	0.67	1.32	-	5.321	37	128.74	36	5.319	19.520	27.737	5.319	-22,418
Pruned coffee	2.771	0.57	1.82	-	2.773	19	69.29	20	2.773	10.177	19.602	2.773	-16,829

Notes

Agroforestry coffee+Monoculture coffee+Pruned coffee, mean C yield on biomass = 4.891 MgC $^{ha-1}$, Mean aboveground carbon yield (MgC $^{ha-1}$) of coffee trees components, calculated from the four (4) allometric equations.

UPS, UDS, RB, FLB and SOC, AGB, understorey, root biomass, litter biomass and soil organic carbon, respectively. CY on biomass total, total carbon yield on biomass is the sum of AGB + RB + FLB (MgC ha^{-1}).

Total C stocks (MgC ha^{-1}) is the sum of CY biomass total and SOC.

Total CO_2 ($MgCO_{2e}$ ha^{-1}) calculated from the total C stocks (MgC ha^{-1}) multiplied by 3.6667 CO_{2e} (CO_2 to carbon ratio).

Net emissions (tCO_{2e} ha^{-1}) is derived from the energy footprint of the individual AFSs measured in liter diesel oil equivalent (LDOE), where 1 LDOE=3.96 kg CO_{2e}.

Net CO_2 sequestered is the difference of the total C stocks ($MgCO_{2e}$ ha^{-1}) less the net emission ($MgCO_{2e}$ ha^{-1}) per three coffee farm patterns.