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# The Effect of Coffee Expansion on Carbon Stock of Natural Forest in Gidame Woreda, West Ethiopia

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**Abstract:** The important climate-related functions of forest ecosystems are carbon sequestration, regulating the global carbon cycle and climate change mitigation. About 80% of the terrestrial carbon is stored as forest biomass and soil organic carbon. Deforestation and forest degradation show an alarming high, mainly due to the conversion of natural forest to commercial and cereal crop production. By considering this issue, this study was conducted with the aim to assess the effect of coffee expansion on carbon stock of the natural forest ecosystem in Gidame woreda. The study site was stratified in two strata: undisturbed natural forest and disturbed coffee forest. A total of 71 nested square sample plot was determined, proportionally allocated (29 for undisturbed and 42 for disturbed/coffee forest) and randomly distributed within each stratum. In both cases, the diameter at breast height and tree height were measured; litter sample was collected by harvesting and weighing technique. A total of 72 composite soil samples were also collected from proportionally and randomly selected 24 sample plots; 10 from undisturbed natural forest and 14 from disturbed coffee forest for SOC quantification in three layers (0-15cm, 16-30cm, and 31-45cm). From these forest inventory data, the above-ground biomass carbon stock was estimated by using allometric equations. The below-ground biomass carbon stock was derived from the above-ground carbon stock. The results showed that the biomass carbon stock was 298.758 ± 9.4tc/ha for undisturbed natural forest and 199.895 ± 11tc/ha for disturbed coffee forest and the difference is statistically significant as $p < 0.05$. This revealed that the disturbance of this natural forest ecosystem, which is associated with the conversion of natural forest to the coffee cultivation area, resulted in the loss of 33.09% of the biomass carbon stock. The SOC is 148.40 ± 12tc/ha for undisturbed forest and 153.80 ± 4.30tc/ha for disturbed coffee forest has no significant difference as $p > 0.05$. Therefore, maintaining the biomass carbon sequestration potential of this natural forest ecosystem should be required through the implementation of different conservation mechanisms.

**Keywords:** Carbon Stock, Coffee Forest, Disturbed Forest, Forest Degradation, Natural Forest, Undisturbed Forest

## 1. Introduction

Natural forest is multilayered vegetation dominated by trees (evergreen or semi-deciduous), who's combined strata overlapping crowns and where grasses in the herbaceous stratum are generally rare [1]. The important climate-related functions of this forest ecosystem are carbon sequestration and carbon storage, which creates carbon stock. These functions are the most faithful option for carbon sequestration, plays a crucial role in regulating the global carbon cycle and climate change mitigation [2]. About 80% of the terrestrial carbon is stored as forest biomass and soil organic carbon [3]. Forest absorbs $CO_2$ gas from the atmosphere through photosynthesis process and stores huge amounts of carbon as biomass that makes up their bark, wood, leaves, and roots when trees are growing. These stored carbon in all living and dead vegetation can be released or emitted in the form of $CO_2$ into the atmosphere by human activities when forests are destroyed either by burning or through deforestation and forest degradation. So, forest acts as the sources and sinks of atmospheric $CO_2$. The emission from deforestation and forest degradation accounts for about 25% of the summed emissions per year [4].

Soil is also the carbon reservoir of the terrestrial carbon cycle next to biomass carbon. Soil carbon sequestration is a process in which $CO_2$ is removed from the atmosphere and stored in the soil carbon pool [5]. About 50% of the soil carbon is stored in forests [6], which include dead organic matter and soil organic matter [7]. Similar to biomass carbon stock, this soil carbon is also exposed and lost to the atmosphere depends upon soil type and management regime. The emitted $CO_2$ into the atmosphere from the destruction of biomass and soil organic carbon contributes to global warming; which occurs from increased atmospheric concentrations of Greenhouse Gases (GHG) leading to the net increase of the global mean temperature [8].

Ethiopia is endowed with its high species diversities in natural forests. Because of its rugged highlands, different agro-ecologies, rainfall pattern and soil variability; it has a huge wealth of biological resources. These are principally attributed to socioeconomic, cultural diversity and complex topography of the country. From these ecological diversities and diversities of plant species in natural forests, the South West Moist Afro-montane forest of Ethiopia is the origin and genetic diversity of *Coffea arabica* species and named as the birthplace of *Coffea Arabica* [9, 10]. As a result, Ethiopia is known as one of the centers of the primary coffee plant domestication country in the world [11].

Even though Ethiopia has different vegetation types and species diversity of natural forests, these natural forest areas with the occurrence of wild coffee gene pools are under constant threats. Legal and illegal deforestation and forest degradation are the most important factors that contribute to social, economic, and environmental challenges facing mankind in the recent century is occurring. This is largely due to anthropogenic factors, including coffee management intensification [12]. From the four coffee production systems, semi-forest coffee and plantation coffee management systems are the major causes of forest degradation in the south west part of the country. Studies [13, 14] show that the semi-forest coffee management system decreases the forest basal area, reduces tree density and eventually leads to the disappearance of the forest tree species. The intensive coffee management under the selected shade trees and the traditional coffee cultivation system, selective cuttings of some tree species which the farmers believe to reduce coffee production affects the biodiversity-based carbon stock [15, 16]. These effects are also being observed in some places in Ethiopia. The only preferred coffee shade trees Albizia gummifera, Acacia abyssinica, and Millettia ferruginea tree species are left in the rich biodiversity of the natural moist evergreen Afro-montane forests of the South West Ethiopia [17, 18].

In the same way in Gidame woreda, the main cause of the problem in the demarcated natural forest area is driven by the need to expand coffee plantation in natural forest. Near to local people only the knowledge of understanding the ongoing processes at the forest margin as deforestation; but not to consider the extent of the persisting forest patch degradation. Land shortage in traditional farming systems, rapid population growth, poor economic performance, and the need for economic growth were increase competition of encroachment among these people and converting natural forest to the coffee cultivation area to improve their livelihood economy. Even though this woreda has high coverage of evergreen moist montane forest, the forest is threatened by the pressure from coffee expansion and there is no study on how this conversion is affecting the carbon stock of natural forest. By considering this issue, this study was conducted with the aim to assess the effect of coffee expansion and its management activities on carbon stock of the natural forest ecosystem in this woreda. Hence, the understanding of human activities which lead to the decline of carbon stock density is the fundamental bases for the development of policies which aim to alter current trends in forest activities toward a more climate and environmental-friendly outcomes.

## 2. Material and Methods

This study was conducted in Gidame woreda, in Kellem Wollega Zone, Oromia Region, Ethiopia, which is located at 688 km west of Addis Ababa. It is bordered on the North by Beghi woreda, on the South by Anfillo woreda, on the East by Jimma Horo woreda, and on the West by South Sudan country. Geographically it is located between 8° 38' 00" N to 9° 12' 00" N Latitude and 34° 10' 00" E to 34° 42' 00" E Longitude, altitude ranges 1500-2300 m ASL and its town Gidame.

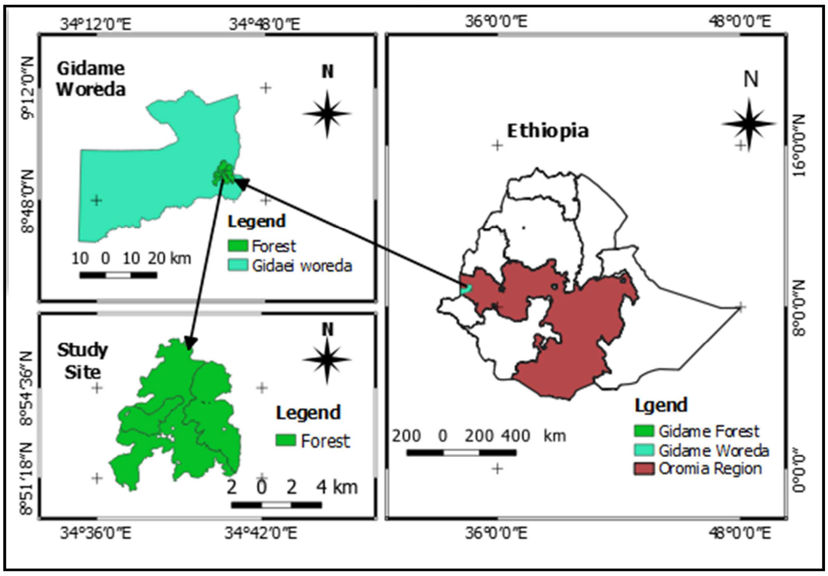


***Figure 1.*** *Map and geographical location of Gidame woreda and the study area of forest.*

The major agro-ecologies of this woreda are 8% Dega, 75% Woina-Dega and 17% Kolla. The maximum temperature ranges from 23 to 26°C with an average annual temperature of 25.2°C and the lowest annual temperature ranges from 7.6–19.8°C with an average of 12.16°C. The rain seasons are spring (March-May), summer (June–August) and autumn (September–November). The average annual rainfall of the district ranges between 941-1635 mm and uni-modal rainfall and 47,004 hectares covered by evergreen moist montane natural forest.

### *2.1. Sources of Data*

To achieve the objective of this study, both primary data and secondary quantitative data was used. The primary data were obtained from the forest inventory based field surveys in the study area of forest which covers four kebeles of the woreda by using a non-destructive data collection technique. The secondary data were obtained from published previous biomass carbon stock assessment journals, thesis and project reports on evergreen moist Afro-montane forests in Ethiopia for representative sample intensity determination.

### *2.2. Sample Size Determination, Sampling Techniques, and Design*

A preliminary survey was carried out within the study area for deciding the proper type of design and intensity of sampling that was appropriate regarding the natural attributes of vegetation type and forest coverage. The boundary and area of the study site were determined and delineated. Naturally, the agro-ecology and vegetation characteristics of this forest ecosystem were no difference except the influences of year to year coffee expansion and management activities. It is dominated by very large trees such as *Aningeria adolfi-friedericii*, Apodytes dimidiata, Albizia gummifera, Olea welwitschii, Strychnos spinosa and consists of other shrubs, lianas and different size tree species composition with different layers of canopies. Thus, the study site was stratified into two strata, or compartments of closed forest (i.e., undisturbed natural forest) and disturbed natural forest (i.e., where converted to coffee) depending upon anthropogenic factors (disturbance history) to make homogeneous characteristics and available for comparison by using GPS. The appropriate simplicity nested square plot-size rules presented in the table 1, that can be applied to any forest research was used for sample plot size, to include all the data of vegetation types, tree size and tree species grown in this natural forest [19].

***Table 1.*** *Nested square plot-size desired and used for forest inventory data collection.*

| Stem diameter and litter | Square plot | Area ($m^2$) |
|---|---|---|
| Litter | 1 m × 1 m | 1 |
| trees 5-20 cm dbh | 7 m × 7 m | 49 |
| Trees 21-50cm dbh | 25 m × 25 m | 625 |
| Trees > 51cm dbh | 35 m × 35 m | 1225 |

After the sample plot shape and area were determined, the required sufficient number of representative sample plot intensities was calculated for adopting a stratified random sampling method by using the next area based formula [20].

$$n = \frac{1}{\frac{1}{N} + \left(\frac{A}{t \times wCV}\right)^2}$$

Where: n = the required total number of sample plots, A = allowable error (10%), t = the sample statistics from the t-distribution for 95% confidence level, t is usually set at 2, N = total number of sampling unit in the study area, and wcv = weighted coefficient of variation 42; it was calculated for both compartments from empirical secondary cruise data sources of previous studies on biomass carbon stock of forest ecosystems in Ethiopia which are similar to forest ecosystem of the present study site. The obtained total sample plots were proportionally allocated depending upon the area coverage of the stratum/compartment as sown in table 2.

***Table 2.*** *Area-based proportional allocation of sample plot intensities estimated for both strata /compartments.*

| Forest compartment | Area (ha) | $N_i$ | Area fraction ($Af_i$) | $CV_i$ | $ni = 71 \times [\frac{Afi \times CVi}{WCV}]$ |
|---|---|---|---|---|---|
| undisturbed natural forest | 2064 | 16849 | 0.4 | 42 | 29 |
| disturbed /coffee forest | 3112 | 25404 | 0.6 | 41 | 42 |
| Total (A, N, wcv and n) | 5176 | 42253 | 1 | 42 | 71 |

Ni= sampling frame, Afi = area fraction, CVi = coefficient of variation for each stratum, ni = number of sample plot for each stratum.

The estimated numbers of sample plots were spatially distributed on base map of the study area by using a stratified random sampling approach for both strata using GRASS QGIS 3.2 version software research tool vector menu as shown in Figure 2. The X and Y coordinates of all these generated sample points were recorded. The field survey checklist was prepared in a table format for measurements of quantitative data. Field note was also used to collect information about the collected data in a written format from observation.

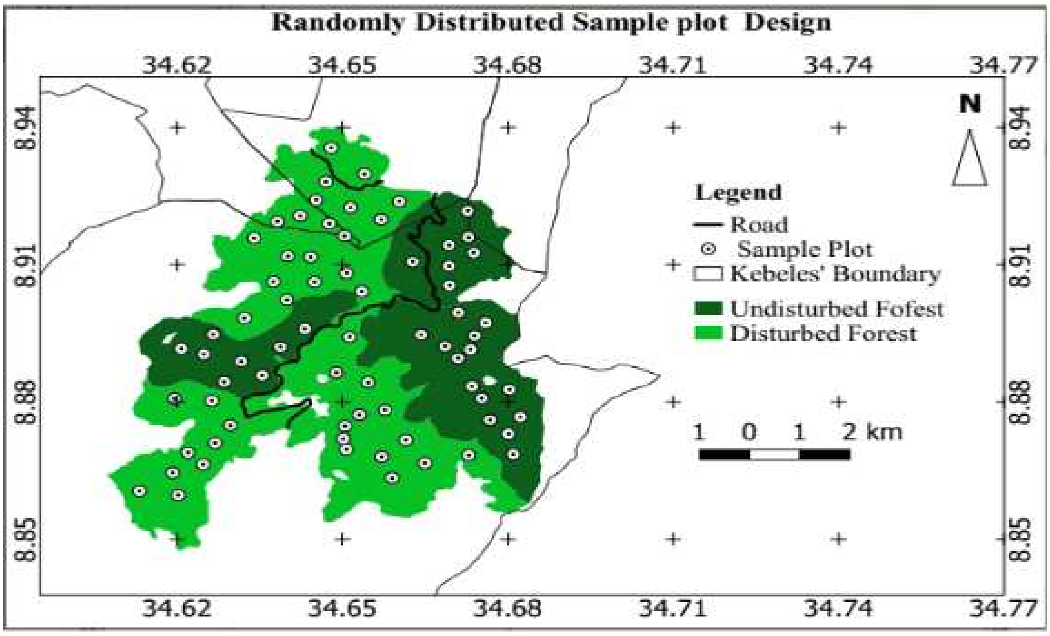


*Figure 2. Randomly distributed sample plots on base map of the study area.*

Plot establishment: The positions of the distributed sample points were found by GPS guide on the ground. Before delineating plot boundaries a simple trigonometric calculation distance on the sloping ground was calculated by the desired length divided by the cosine of the angle of the slope (d = 35 m/cos θ) in the field for slope correction using a clinometer for inclined surface. Then the desired concentric nested square plots were constructed on the ground by using meter tape and rope.

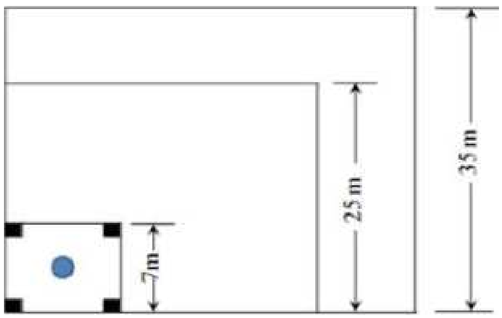


***Figure 3.*** *Layout of sample plot design on the ground used for data collection.*

### *2.3. Data Collection*

The parameters needed to estimate above-ground biomass, diameter at breast height (DBH) and tree height (H) were measured by using diameter tape and hypsometer. For trees and coffees with multiple forks begin below 1.30 m, shrubs near to the ground or at collar and 0.40 m height respectively, the DBH of each fork were measured separately. plant species starting from small to large, living trees, climbers/Lianas, shrubs which are greater than 3 m in height and diameter classes of 5 cm to 20 cm DBH, 21-50 cm DBH, and greater than 51 cm DBH in the nested sample plots were properly measured and recorded separately according to their stem diameter class specified in desired plot size. All the trunks, dead standing trees, dead trees lying on the ground that have a diameter >10 cm and a length of > 0.5 m were sampled were they considered as dead [21]. Their length and diameter halfway/at the middle length were measured [22] from subplot of 25 m × 25 m; as well as notes identifying the types of wood for finding their specific wood densities were registered. Forest floor litter data was collected by simply harvesting and weighing technique from 1m$^2$ of the nested square plots. The weight of the fresh mass of the liter sample was weighed and recorded. After air dried, the weight was determined by weighing and recording again for analysis.

In both undisturbed natural forest and disturbed coffee forest of the study area, the soil samples were collected from 24 sub-sample plots. 10 sample plots from undisturbed forest and 14 sample plots from a disturbed coffee forest in proportion to their area coverage of the stratum at three depth layers of 0 - 15 cm, 16 - 30 cm, and 31 - 45 cm after removing the upper litter from four corners of the (7 x 7) m nested square sample plot. A composite 72 soil samples were proportionally (10 plots x 3 depths and 14 × 3 depths) taken for SOC content analysis with the help of a metal soil sampling corer. Stones and plant residues were removed from the soil samples and a 300 g was taken for one layer by mixing and making homogeneous. From three-layer depths of one plot, 900 g of soil sample was collected. A sampler with internal 5 cm diameter core and 15 cm height steel cutting was used for sample taking to determine soil bulk density (SBD) in each of three soil depths (0 -15 cm, 16 -30 cm, and 31- 45 cm) from the center point of the diagonals of the square plot of (7 x 7) m. The original volume of each soil core was measured and recorded in each three layers. The collected soil samples were brought to Wondo Genet College of Forestry and Natural Resource soil laboratory for analysis of bulk densities and percent of soil carbon contents.

### *2.4. Data Analysis*

The forest inventory data and soil data were analyzed and interpreted using quantitative statistics. The independent two sampled t-test was performed to determine whether there were significant differences between forest classes' carbon stocks. The statistical tests for significance of differences were tested using the Least Significant Difference (LSD) of mean at $p < 0.05$. Descriptive statistics percentage and tables were employed to summarize the results with the forest disturbance indicators and supported with concise discussion.

The above-ground biomass of all sampled individual trees were calculated by using the Pan tropical mixed-species, broad-leaf allometric model, which was usually yield less biased estimate with the inclusion of the country's specific wood density and tree height, for dry biomass estimation; $AGB = 0.0673\times(WD\times DBH^2\times H)^{0.976}$ [23]. Lianas Biomass = exp(0.12+ 0.91 log (BA at DBH)) [24]. For coffee plant's' biomass estimation, species-specific allometric equation above ground *Coffea arabica* biomass = $0.147d^2_{40}$ [25] was used. Where: AGB = above ground biomass (in kg dry matter), WD = wood density ($g/cm^3$), DBH =Diameter at Breast Height (cm), H = total height of the tree (m), BA = basal area at 1.3 m height ($m^2$), and ($d_{40}$) is diameter at 40 cm height used for only coffee. Biomass of shrub and saplings was calculated using the following allometric equation [26], *ln* (AGBs) = -3.50 + 1.65 × *ln* (D) + 0.842 × *ln* (H), where: AGBs =Shrub above ground biomass (kg); D =Collar diameter (cm); and, H=Total height (m).

The biomass of standing dead trees which have no leaves 2.5% subtraction of dry biomass; for dead trees contain only large branches or no branches biomass was reduced by 20% above-ground dry biomass and biomass of downed deadwood was estimated using two decomposition levels [7]: Sound (the blade does not sink or is bounced off) and has a decomposition level value of 0.90 and Rotten (blade sinks well into the piece, there is extensive wood loss and the piece is crumbly) and has a decomposition level value of 0.50. Biomass of LDW = V× 90% ×WD for sound and Biomass of LDW = V × 50% ×WD for rotten. Where LDW = Lying Dead Wood, V= volume and WD = specific wood density ($0.615g/cm^3$). Volume ($m^3$) = $\pi^2 d^2 / (8 \times L)$ Where: d = have way diameter of dead wood intersecting the line (cm). L = the length of the line, in meters (100m). The amount of litter biomass per hectare of forest floor was analyzed by using the ratio of dry weight to the fresh weight method [27].

$$\mathrm{LMB} = \frac{W\,field}{A} \times \frac{W\,sub\,sample\,dry}{W\,sub\,sample\,wet} \times 10000$$

Where LBM = biomass of leaf litter (t/ha), W field = weight of the fresh field sample of litter sampled within an area of size A (g), A = size of the area in which litter was collected ($m^2$), W sub-sample, dry = weight of the dried sub-sample of litter (g), W sub-sample, wet = weight of the fresh sub-sample of litter (g). The carbon content in the litter biomass was converted from dry mass to carbon by multiplying conversion factor 37% [7].

Below ground biomass carbon stock was estimated by using a suitable R:S (root to shoot) ratio established as default value for global application that expresses root biomass with above-ground biomass since it is often difficult to measure directly. Root biomass = 27% × AGB [7]. To express the dry weight biomass in carbon stock, the estimated above-ground and below-ground dry biomasses were multiplied by the conservative default value of carbon fraction 47% [7].

The soil samples collected for bulk density were oven-dried at a temperature of 105°C for 48 hours and weighed [19, 27] in soil laboratory. The dried and weighed soil samples were washed through 2 mm sieve with water until substantially clean water came out. The washed soil fragments were oven-dried again normally for 24 hours to remove water moisture. The mass of these dried fragments was weighed. The volume and density of coarse fragments were determined. The fine bulk density was calculated for three layers of samples (0–15 cm, 16–30 cm and 31–45 cm) for each plot by using formula.

$$Fine\ bulk\ density(g/cm^3) = \frac{Oven\ dry\ mass(g)}{Core\ volume(cm^3) - \left[\frac{Mass\ of\ coarse\ fragments(g)}{Density\ of\ coarse\ fragments(g/cm^3)}\right]}$$

The composite soil samples were air-dried, sieved in 2 mm sieve and SOC concentration (%) were quantified using [28] method from the composite soil samples. The amount of soil carbon stock per hectare area was calculated from fine soil bulk density, carbon concentration (%) data obtained from laboratory analysis and soil depth.

SOC (tc/ha) = [(soil bulk density ($g/m^3$) x soil depth (cm) x C %)] x 100 (source: [19]).

## 3. Results

### *3.1. Biomass Carbon Stock*

The DBH and height of 426 individual trees from 37 species were measured and recorded with a maximum diameter of 131 cm (*Ekebergia capensis*) and in the undisturbed natural forest. The average basal area of 37.52 $m^2$/ha (minimum 19.42 $m^2$/ha and a maximum 65.42 $m^2$/ha) was determined. In the same way, the DBH and height of 279 individual trees were also measured according to their diameter classes from 25 tree species in a disturbed coffee forest stratum. In addition to these, for biomass carbon stock estimation, the DBH of 359 coffee plants were measured at 40 cm height from the ground surface level. The maximum diameter recorded in the coffee forest was 127 cm (*Aningeria adolfi-friederici*) with an average basal area of 28.92 $m^2$/ha (minimum 9.22 $m^2$/ha and maximum 48.47 $m^2$/ha). These field inventory data showed that plant species density and basal area were higher in an undisturbed natural forest as compared to the disturbed coffee forest. With expanding coffee plantation and its management activities, the forest stand characteristics, tree density and basal area of natural forest ecosystem were declined.

***Table 3.*** *Mean biomass carbon stock (tc/ha) ±SE in the undisturbed natural forest and disturbed coffee forest paired t-test comparison.*

| Biomass carbon pools | Undisturbed natural forest (n = 29) | | | Disturbed coffee forest (n= 42) | | | T | P |
|---|---|---|---|---|---|---|---|---|
| | AGC | BGC | Total | AGC | BGC | Total | | |
| trees, lianas and shrubs | 233.92 ±7.223[a] | 63.158 ± 1.974[a] | 297.078 ± 9.197[a] | 147.672 ± 7.746[b] | 39.871 ± 2.20[b] | 187.543 ± 9.946[b] | 6.38 | 0.000 |
| coffee | 0.094 ± 0.094[b] | 0.025 ± 0.026[b] | 0.119 ± 0.12[b] | 8.58 ± 0.75[a] | 2.320 ± 0.2[a] | 10.90 ± 0.95[a] | 9.56 | 0.000 |
| dead wood | 0.435 ± 0.046 | - | 0.435 ± 0.046 | 0.689 ± 0.073 | - | 0.689 ± 0.073 | 1.63 | 0.109 |
| litter | 1.126 ± 0.037[a] | - | 1.126 ± 0.037[a] | 0.763 ± 0.031[b] | - | 0.763 ± 0.031[b] | 7.51 | 0.000 |
| Total | 235.575 ± 7.40[a] | 63.183 ± 2[a] | 298.758 ± 9.40[a] | 157.704 ± 8.6[b] | 42.191 ± 2.40[b] | 199.895 ± 11[b] | 6.39 | 0.000 |

Different letters show that the difference is significant at $p < 0.05$.

The estimated mean biomass carbon stock density was higher in undisturbed natural forest carbon pool components than that of a disturbed coffee forest. The two-sampled t-test comparison test revealed that there was a significant difference (expressed at 95% confidence interval of the mean) between the two stratum of forest ecosystem biomass carbon stock ($T = 6.39$ and $P < 0.05$). The disturbance of this natural forest ecosystem, which associated with the conversion of natural forest to the coffee cultivation area, resulted in the loss of 33.09% of the biomass carbon stock. The biomass carbon stock density results obtained from both forest classes of this study area were larger, consistent and comparable to earlier studies in Ethiopia and other tropical countries. They fall within the ranges reported for undisturbed and disturbed forest biomass carbon stock across in the different tropical forest ecosystem.

***Table 4.*** *Mean (± SE) of soil organic carbon content (%) and mean soil fine bulk densities at different soil depths in Gidame woreda forest ecosystem.*

| undisturbed forest | | | disturbed coffee forest | |
|---|---|---|---|---|
| Soil depth (cm) | fine BD (g/cm$^3$) | SOC content (%) | fine BD (g/cm$^3$) | SOC content (%) |
| 0-15 | 0.743 ± 0.0525 | 5.919 ± 0.555 | 0.793 ± 0.0193 | 5.801 ± 0.346 |
| 16-30 | 0.788 ± 0.0536 | 3.814 ± 0.435 | 0.812 ± 0.0175 | 3.738 ± 0.229 |
| 31-45 | 0.818 ± 0.0394 | 3.041 ± 0.269 | 0.821 ± 0.0212 | 3.191 ± 0.116 |

### *3.2. Soil Organic Carbon Stock*

In both forest classes, the average soil bulk density of the study site increased with the depth increment. The conversion of natural forest to forest coffee caused soil bulk density increase mostly in the upper soil layer as compared to undisturbed natural forest class. The quantified carbon contents of the soil in the study area range from 2.98–7.85%, 2.38–6.50% and 1.81–4.41% in 0–15 cm, 16–30 cm and 31–45 cm soil layer respectively for the undisturbed natural forest. The soil carbon content ranges from 3.92–8.40%, 2.53–5.78% and 2.53–3.97% in 0–15 cm, 16–30 cm and 31–45 cm soil layer respectively in the disturbed coffee forest. This shows that the concentration (%) of soil organic carbon was decreased in different rates with increasing soil depth in both forest classes. The summary of mean soil organic carbon contents (%) mean fine bulk densities and their standard deviation in different soil depths was presented in table 4 for both forest types.

The investigated soil organic carbon stocks for 0–45 cm layers were 148.40tc/ha from undisturbed natural forest and 153.80tc/ha from disturbed forest coffee. In contrast to biomass carbon stocks, the mean soil organic carbon stock was higher for the disturbed coffee forest and lower for the undisturbed natural forest. However, the difference between these forest types in SOC did not show significant variation ($T = 0.48$; $P > 0.05$) at the ecosystem level. The insignificant amount of soil organic carbon stock difference in 0–15 cm upper and 31-45 cm lower soil layer caused by the increment of soil bulk density rather than soil organic carbon contents. But there was no difference in soil organic carbon stock in the middle soil layer.

***Table 5.*** *Mean soil organic carbon stock (tc/ha) distribution in different soil depths in the Gidame district forest ecosystem.*

| Undisturbed forest | | | Disturbed / coffee forest | | | |
|---|---|---|---|---|---|---|
| Soil depth (cm) | N | Mean ± SE | N | Mean ± SE | T-value | P-value |
| 0-15 | 10 | 66.00 ± 6.20 | 14 | 69.00 ± 4.10 | 0.43 | 0.675 |
| 16-30 | 10 | 45.10 ± 5.10 | 14 | 45.50 ± 2.80 | 0.08 | 0.935 |
| 31-45 | 10 | 37.30 ± 3.30 | 14 | 39.30 ± 1.40 | 0.61 | 0.546 |
| 0-45 | 30 | 148.40 ± 12 | 42 | 153.80 ± 4.30 | 0.48 | 0.636 |

# 4. Discussion

### *4.1. Biomass Carbon Stock*

The total biomass carbon stock in an undisturbed natural forest of this study was greater than biomass carbon stock in the tropical wet zone of the Sigiriya forest sanctuary, forest reserve in Sri Lanka 249tc/ha [29] and Gesha moist Afro-montane forest in Kaffa Zone, South-Western Ethiopia 225.92tc/ha [30], compared with 298.77tc/ha for GerbaDima moist Afro-montane forest, South-Western Ethiopia [31]. But it was lower than the least disturbed wet evergreen rainforest of Eastern Himalaya 425.70tc/ha [32] and other forest ecosystem Egdu dry Afro-montane forest 333.70tc/ha [33]. The biomass carbon stock found from the disturbed coffee forest of this study was also comparable to biomass carbon stock of Giza-Sayilem moist Afro-montane forest in Kaffa Zone, South-West Ethiopia 198.67tc/ha [34], greater than Tankawati forest of Bangladesh 115.3tc/ha [35]. But less than mild disturbed 236.08tc/ha and greater than highly disturbed 127.38tc/ha wet evergreen rainforest of Eastern Himalaya [32]. The causes of these variations between forest types of the study areas, biomass carbon stock was might be caused by different degrees of anthropogenic disturbance, models used to estimate biomass, presence of bigger sized trees in the higher basal area, ecological variation, and higher densities of woody species or vegetation characteristics.

As shown in Table 3 the above-ground biomass carbon stock in undisturbed natural forest was higher than that of disturbed coffee forest above-ground biomass carbon stock. This revealed that the carbon sequestration potential of this natural forest was decreased with expanding and converting to the coffee cultivation area. The two sampled comparison statistical test ($T = 6.38$ and $P < 0.05$) shows that the above-ground biomass carbon stock of this forest ecosystem was significantly differed between both forest stratum. The effect of this change in forest biomass carbon stock was mostly from the loss of above-ground living trees and replacing with coffee. Based on the estimation of forest inventory data, the most substantial amount of carbon is stored in the living biomass of aerial plant parts. The removal of these living biomass of aerial plant parts and replacing with the coffee plantation caused the loss of 26.06% of the total biomass carbon stock density. The result of biomass carbon stock in this forest was an essential indicator of living tree parts' productive capacity to sequester a high amount of carbon and sources of high carbon dioxide emission due to human disturbance.

This study confirms that the conversion of natural forest ecosystem to other land uses, modification and loss of forests due to disturbances were the large source of human-induced climate change, which accounted 6–20% of anthropogenic greenhouse gas emissions [36-39]. Forest disturbance influences the amount of forest carbon stock through by altering the stand structure and composition [40]. The living vegetation, the largest above-ground carbon pool was extremely sensitive to disturbance. It was particularly affected by human disturbance, exhibiting the large decrease in carbon stock density [41]. Another study [42] also showed that forest degradation leads to biomass loss. This loss or reduction of forest biomass carbon stock was mainly driven by conversion to other land uses and forest degradation [43]. 90 percent of the forest can be cleared before it is considered deforested; as such, forest degradation can lead to substantial carbon emissions and is often an important precursor to deforestation [44].

In the study area, it is also observed that a significant number of coffee farmers have expanded a clearance of woody, herbaceous and Lianas or climbers vegetation to get free space for coffee plantations. This is similar to other study the site with high coffee cover had a lower coverage of lines and climbing vines [45]. Forest coffee management has predominantly done through undertaking the operations slashing undergrowth vegetation, cutting, debarking, removing under-story vegetation and selective thinning of shade trees depending upon the necessities and requirements of sunlight to maintain optimum shade for coffee production. Those tree species with many trunks, big/broad leaves, and dense canopies were debarked and burn around the root collar area. The only preferred coffee shade trees were left to maintain the production and productivity of coffee yields. The selective cutting of some none preferred tree species in the human-modified landscape during coffee management affected the ecological functions and/or ecosystem service carbon sequestration potential of the natural forest terrestrial ecosystem.

The nonliving forest floor litter and dead wood biomass carbon contribute a tiny and insignificant percentage of biomass carbon to this forest ecosystem. Even though the non-living biomass carbon stock density in dead woods and litter of the study site were low, it was a component of above-ground biomass. In undisturbed natural forest deadwood performs several important ecological functions for many forest-dwelling species [46]. The standing and downing dead woods of large trees also ultimately enhancing ecosystem function, including protection of soil nutrient retention [47]. The lowest carbon stock in the forest floor litter might probably the rate of litter decomposition [31]. Where the study area is located in tropical areas, the rate of decomposition is relatively fast [48].

The derived mean of below-ground biomass carbon stock in undisturbed natural forest was significantly higher than that of coffee forest($T = 6.43$ and $P < 0.05$ at 95% confidence interval). In this study, the mean difference between both below-ground biomass carbon stock was 20.10 tc/ha. This difference showed that the destruction of root biomass caused by coffee plantation and its management activities lead to a loss of 7.03% tc/ha from the total biomass carbon stock of the forest ecosystem. This confirms that the loss of below-ground biomass carbon stock due to the conversion of natural forest to coffee by removing aerial living vegetation [49]. As compared to other studies the obtained result of below-ground biomass carbon stock from undisturbed natural forest of this study was greater than 45.97 tc/ha below ground carbon sock of Gerba-Dima moist Afro-montane forest, South-Western Ethiopia [31]. The BGBC result for disturbed or coffee forest was also greater than 34.3tc/ha below-ground carbon sock of moist Afro-montane forest in Gesha district in Kaffa South-West Ethiopia [34] and contributed a significant amount of biomass carbon to the ecosystem next to the soil carbon pool.

### *4.2. Soil Organic Carbon Stock*

The SOC stock found from undisturbed natural forest in two layers (0–30) cm soil depths of this study was less than 162.62tc/ha (0–30) cm depths of soil carbon stock of Gerba-Dima moist Afro-montane forest, South-Western Ethiopia [31], 128tc/ha soil carbon sock in 0-15 cm and 15-30 cm layers for moist Afro-montane forest in Gesha District in Kaffa [34]. But greater than Gera native forest SOC stock 98.95tc/ha and coffee-based agroforestry SOC stock 94.30tc/ha in South-Western Ethiopia [50], 88.40tc/ha in 0-15 cm and 15-30 cm layers of old-growth montane forest in lower montane Ecuador [51], 79.01tc/ha and 99.65tc/ha of the natural forests at Me Linh biodiversity station, Vinh Phuc province in Vietnam [52], 106.17tc/ha for Geza and lower than 160.00 tc/ha for Mtimbwani forest ecosystem in Tanga, Tanzania [53].

The differences of these SOC between different studying area's forest ecosystems caused from the differences of vegetation characteristics, different management activities in native forest, soil type and soil properties, history of land use land cover and other environmental and climatic factors. Other studies considered that the amount of soil organic carbon is influenced by relief, soil texture; high soil water content tends to conserve soil organic matter and temperature accelerates biological processes [54, 55]. Dead organic matter on the ground and plant biomass below the ground to decompose and transform into soil organic matter, and can have varying residence times in the soil [5]. The declined of mean soil carbon stock of this study when the depth and soil bulk density increased in both forest classes agreed with other earlier studies that soil organic carbon content was higher at the surface than in the deeper soil layers [56], and decreasing trend with soil depth [57]. In contrast, as soil depth and bulk density increased, the percentage of soil carbon contents decreased [51]. The majority of Soil Organic Carbon (SOC) is found primarily in the upper layer because it is the most biologically active [58].

The interactions among different species of vegetation were essential to maintain soil quality, ecological, and landscape integrity [59]. The old-growth forests accumulated large quantities of carbon stock for centuries and contain much soil carbon content [60], which will move back to the atmosphere or decomposed when forests were disturbed [61]. The soil organic carbon content depends upon land management, and land uses. The higher carbon stock density in the upper soil layer of coffee plantation can be explained by soil compaction and by compensation of reduced Soil Organic Carbon (SOC) inputs from litter and debris by increased soil enrichment [62].

In the study site, farmers remove some shade trees and increase the penetration of sunlight to the forest floor for optimizing light and heat for coffee production. This might increase the ground surface temperature and the abundance of some dead wood on the forest floor. This predicts an average of deadwood and litter [63] where soil organic carbon is a balance between the input of surface litter (fallen leaves and dead organisms) and the rate at which microbes break down organic compounds [64]. However, increasing temperatures could reduce SOC by accelerating the microbial decomposition [55]. Moderate to heavy disturbance in tropical moist forests has a profound impact on fine root turnover and the related carbon transfer to the soil [65]. On the other hand, increasing SOC levels can be achieved by increasing carbon inputs to soils. In the case of managed soils, this can be done by increasing the input and retention of above-ground biomass [55]. In general, the results of this study revealed that soil carbon stock did not show a significant variation between natural forests and tropical Agroforestry landscapes [66].

## 5. Conclusion and Recommendations

Coffee expansion and its management activities decrease forest characteristics: basal area and tree density which lead to minimize biomass carbon stock from 298.758 ± 9.40tc/ha to 199.895 ± 11tc/ha in this study. This indicated that the loss of 33.09% (26.06% from ABC and 7.03% from BBC) biomass carbon stock from the natural forest converted to coffee forest. But the estimated soil organic carbon stock 148.40 ± 12tc/ha for undisturbed forest and 153.80 ± 4.30 tc/ha for disturbed coffee forest in 0–45 cm soil profiles didn't show significant variation and the soil organic carbon stock of the study site was not affected due to coffee expansion. Therefore, the results of this study strictly indicated that the conservation of this natural forest ecosystem, enhancing its carbon sequestration potential should be widely recognized and needs further investigation. Regular assessment of biomass carbon stock of this natural forest should be made on its own operational plan. Reducing coffee expansion in this natural forest which destructs the biomass carbon stock of this natural forest and enhancing prioritization of forest conservation through local community participation and provision of environmental awareness for forest user groups should be provided. The attention on the need to achieve sustainable forest management should be adopted for the ecosystem service of biodiversity-based carbon sequestration potential of this forest.

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## References

[1] Geldenhuys CJ. Concepts and Process to Control Invader Plants in and Around Natural Evergreen Forest in South Africa1. Weed Technology. 2004 Dec; 18 (sp1): 1386-91.

[2] Virgilio N, Marshall S. Forest carbon strategies in climate change mitigation: confronting challenges through on the-ground experience. The Nature Conservancy. Arlington, Virginia. 2009.

[3] Hamdan O, Aziz HK, Rahman KA. Remotely sensed L-Band SAR data for tropical forest biomass estimation. Journal of Tropical Forest Science. 2011 Jul 1: 318-27.

[4] Pearson TR. Measurement guidelines for the sequestration of forest carbon. US Department of Agriculture, Forest Service, Northern Research Station; 2007.

[5] Ontl TA, Schulte LA. Soil carbon storage. Nature Education Knowledge. 2012; 3 (10).

[6] Tremblay S, Périé C, Ouimet R. Changes in organic carbon storage in a 50 year white spruce plantation chronosequence established on fallow land in Quebec. Canadian journal of forest research. 2006 Nov 1; 36 (11): 2713-23.

[7] Change IP. 2006 IPCC guidelines for national greenhouse gas inventories. Institute for Global Environmental Strategies, Hayama, Kanagawa, Japan. 2006.

[8] Bhartendu A. Deforestation causing global warming and climate change. International Journal of Chemical Sciences. 2012; 10 (3): 1731-4.

[9] WeldeMichael G, Alamerew S, Kufa T. Genetic Diversity Analysis of Some Ethiopian Specialty Coffee (*Coffea arabica* L.) Accessions for Cup Quality Attributing Traits. J. of Biology, Agriculture and Healthcare. 2015; 5 (5): 88-96.

[10] Mishra MK, Nishani S, Gowda M, Padmajyothi D, Suresh N, Sreenath H, Raghuramulu Y. Genetic diversity among Ethiopian coffee (*Coffea arabica* L.) collections available in Indian gene bank using sequence related amplified polymorphism markers. Plant breeding and seed science. 2014 Dec 18; 70: 29-40.

[11] Engels JM, Hawkes JG, Hawkes JG, Worede M, editors. Plant genetic resources of Ethiopia. Cambridge University Press; 1991 Mar 21.

[12] Taye K. Plant composition and growth of wild *Coffea arabica*: Implications for management and conservation of natural forest resources. International Journal of Biodiversity and Conservation. 2011 Apr 30; 3 (4): 131-41.

[13] Senbeta F, Denich M. Effects of wild coffee management on species diversity in the Afromontane rainforests of Ethiopia. Forest Ecology and Management. 2006 Aug 15; 232 (1-3): 68-74.

[14] Hundera K, Aerts R, Fontaine A, Van Mechelen M, Gijbels P, Honnay O, Muys B. Effects of coffee management intensity on composition, structure, and regeneration status of Ethiopian moist evergreen afromontane forests. Environmental management. 2013 Mar; 51 (3): 801-9.

[15] Aerts R, Hundera K, Berecha G, Gijbels P, Baeten M, Van Mechelen M, Hermy M, Muys B, Honnay O. Semi-forest coffee cultivation and the conservation of Ethiopian Afromontane rainforest fragments. Forest Ecology and Management. 2011 Mar 15; 261 (6): 1034-41.

[16] Basnyat B. Impacts of demographic changes on forests and forestry in Asia and the Pacific. Bangkok, FAO of the United Nations Regional Office for Asia and the Pacific. 2009.

[17] Hundera K. Effects of Coffee Forest Management and Fragmentation on Plant Communities and Regeneration Patterns In Afromontane Moist Evergreen Forests in South West Ethiopia. Jimma University. 2013.

[18] Hundera K. Shade tree selection and management practices by farmers in traditional coffee production systems in Jimma Zone, Southwest Ethiopia. Ethiopian Journal of Education and Sciences. 2016; 11 (2): 91-105.

[19] Pearson T, Walker S, Brown S. Sourcebook for land use, land-use change and forestry projects.

[20] Avery TE, Burkhart HE. Forest measurements. Waveland Press; 2015 May 18.

[21] Hairiah K, Sitompul SM, Van Noordwijk M, Palm C. Methods for sampling carbon stocks above and below ground. Bogoi: ICRAF; 2001 Dec.

[22] Bhishma PS, Shiva SP, Ajay P, Eak BR, Sanjeeb B, Tibendra RB, Shambhu C, Rijan T. Forest Carbon Stock Measurement: Guidelines for measuring carbon stocks in community-managed forests. Funded by Norwegian Agency for Development Cooperation (NORAD). Asia Network for Sustainable Agriculture and Bioresources (ANSAB) publishing, Kathmandu, Nepal. 2010: 17-43.

[23] Chave J, Réjou-Méchain M, Búrquez A, Chidumayo E, Colgan MS, Delitti WB, Duque A, Eid T, Fearnside PM, Goodman RC, Henry M. Improved allometric models to estimate the aboveground biomass of tropical trees. Global change biology. 2014 Oct; 20 (10): 3177-90.

[24] Putz FE. Liana biomass and leaf area of a" tierra firme" forest in the Rio Negro Basin, Venezuela. Biotropica. 1983 Sep 1: 185-9.

[25] Negash M, Starr M, Kanninen M, Berhe L. Allometric equations for estimating aboveground biomass of *Coffea arabica* L. grown in the Rift Valley escarpment of Ethiopia. Agroforestry systems. 2013 Aug; 87 (4): 953-66.

[26] DeWalt SJ, Chave J. Structure and biomass of four lowland Neotropical forests. Biotropica. 2004 Mar; 36 (1): 7-19.

[27] Karki S, Joshi NR, Udas E, Adhikari MD, Sherpa S, Kotru R, Karky BS, Chettri N, Ning W. Assessment of forest carbon stock and carbon sequestration rates at the ICIMOD Knowledge Park at Godavari. ICIMOD Working Paper. 2016 (2016/6).

[28] Walkley A, Black IA. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil science. 1934 Jan 1; 37 (1): 29-38.

[29] Kuruppuarachchi KA, Seneviratne G, Madurapperuma D. Carbon sequestration in tropical forest stands: its control by plant, soil and climatic factors.

[30] Addi A. The Ecology, Carbon Stock, Bee Forage diversity In A Moist Afromontane Forest Of Gesha And Sayilem Districts In Kaffa Zone, South West Ethiopia. J. Mater. Process. Technol. 2018.

[31] Dibaba A, Soromessa T, Workineh B. Carbon stock of the various carbon pools in Gerba-Dima moist Afromontane forest, South-western Ethiopia. Carbon balance and management. 2019 Dec; 14 (1): 1-0.

[32] Sahoo A. Assessment of Biomass and Total Carbon Stock in a Tropical Wet Evergreen Rainforest of Eastern Himalaya along a Disturbance Gradient. Assessment. 2017 Apr; 4 (1).

[33] Feyissa A, Soromessa T, Argaw M. Forest carbon stocks and variations along altitudinal gradients in Egdu Forest: Implications of managing forests for climate change mitigation. Science, Technology and Arts Research Journal. 2013; 2 (4): 40-6.

[34] Addi A, Demissew S, Soromessa T, Asfaw Z. Carbon stock of the moist Afromontane forest in Gesha and Sayilem Districts in Kaffa Zone: An implication for climate change mitigation. J Ecosyst Ecograph. 2019; 9 (1): 1-8.

[35] Ullah MR, Al-Amin M. Above-and below-ground carbon stock estimation in a natural forest of Bangladesh. Journal of forest science. 2012 Aug 24; 58 (8): 372-9.

[36] Baccini AG, Goetz SJ, Walker WS, Laporte NT, Sun M, Sulla-Menashe D, Hackler J, Beck PS, Dubayah R, Friedl MA, Samanta S. Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. Nature climate change. 2012 Mar; 2 (3): 182-5.

[37] Gullison RE, Frumhoff PC, Canadell JG, Field CB, Nepstad DC, Hayhoe K, Avissar R, Curran LM, Friedlingstein P, Jones CD, Nobre C. Tropical forests and climate policy. Science. 2007 May 18; 316 (5827): 985-6.

[38] Harris NL, Brown S, Hagen SC, Saatchi SS, Petrova S, Salas W, Hansen MC, Potapov PV, Lotsch A. Baseline map of carbon emissions from deforestation in tropical regions. Science. 2012 Jun 22; 336 (6088): 1573-6.

[39] Change IP. Report of The Nineteenth Session Of The Intergovernmental Panel on Climate Change (IPCC) Geneva, 17-20 (am only) April 2002.

[40] Thong P, Pebam R, Sahoo UK. Recovery pattern of vegetation during succession following slash and burn agriculture in Mizoram, North-East India. Journal of Plant Biology and Soil Health. 2016; 3 (2): 8-16.

[41] Berenguer E, Ferreira J, Gardner TA, Aragão LE, De Camargo PB, Cerri CE, Durigan M, Oliveira RC, Vieira IC, Barlow J. A large-scale field assessment of carbon stocks in human-modified tropical forests. Global change biology. 2014 Dec; 20 (12): 3713-26.

[42] Chidumayo EN. Forest degradation and recovery in a miombo woodland landscape in Zambia: 22 years of observations on permanent sample plots. Forest Ecology and Management. 2013 Mar 1; 291: 154-61.

[43] MacDicken K, Jonsson Ö, Piña L, Maulo S, Contessa V, Adikari Y. & D'Annunzio, R. (2016). Global forest resources assessment. 2015.

[44] Virgilio NR, Marshall S, Zerbock O, Holmes C. Reducing emissions from deforestation and degradation (REDD): a casebook of on-the-ground experience. Reducing emissions from deforestation and degradation (REDD): a casebook of on-the-ground experience. 2010.

[45] Hylander K, Nemomissa S, Delrue J, Enkosa W. Effects of coffee management on deforestation rates and forest integrity. Conservation biology. 2013 Oct; 27 (5): 1031-40.

[46] Lassauce A, Paillet Y, Jactel H, Bouget C. Deadwood as a surrogate for forest biodiversity: meta-analysis of correlations between deadwood volume and species richness of saproxylic organisms. Ecological Indicators. 2011 Sep 1; 11 (5): 1027-39.

[47] Franklin JF, Spies TA, Van Pelt R, Carey AB, Thornburgh DA, Berg DR, Lindenmayer DB, Harmon ME, Keeton WS, Shaw DC, Bible K. Disturbances and structural development of natural forest ecosystems with silvicultural implications, using Douglas-fir forests as an example. Forest ecology and management. 2002 Jan 1; 155 (1-3): 399-423.

[48] Binkley D, Fisher RF. Ecology and management of forest soils. John Wiley & Sons; 2019 Jun 10.

[49] Barbosa RI, dos Santos JR, da Cunha MS, Pimentel TP, Fearnside PM. Root biomass, root: shoot ratio and belowground carbon stocks in the open savannahs of Roraima, Brazilian Amazonia. Australian Journal of Botany. 2012 Jul 11; 60 (5): 405-16.

[50] Mohammed A, Bekele L. Changes in carbon stocks and sequestration potential under native forest and adjacent land use systems at gera, south-western Ethiopia. Global Journal of Science Frontier Research: D Agriculture and Veterinary. 2014 Jan; 14 (10): 11-9.

[51] Rhoades CC, Eckert GE, Coleman DC. Soil carbon differences among forest, agriculture, and secondary vegetation in lower montane Ecuador. Ecological Applications. 2000 Apr; 10 (2): 497-505.

[52] Dang TT, Do HT. Biomass and carbon stocks of the natural forests at Me Linh biodiversity station, Vinh Phuc province, Vietnam. Journal of Vietnamese Environment. 2014 Nov 5; 6 (3): 281-7.

[53] Alavaisha E, Mangora MM. Carbon stocks in the small estuarine mangroves of Geza and Mtimbwani, Tanga, Tanzania. International Journal of Forestry Research. 2016 Jan 1; 2016.

[54] Batjes NH. Soil organic carbon stocks under native vegetation–Revised estimates for use with the simple assessment option of the Carbon Benefits Project system. Agriculture, Ecosystems & Environment. 2011 Aug 1; 142 (3-4): 365-73.

[55] Victoria R, Banwart S, Black H, Ingram J, Joosten H, Milne E, Noellemeyer E, Baskin Y. The benefits of soil carbon. Foresight chapter in UNEP Yearbook. 2012; 2012: 19-33.

[56] Zhang Z, Zhou Y, Wang S, Huang X. Estimation of soil organic carbon storage and its fractions in a small karst watershed. Acta Geochimica. 2018 Feb; 37 (1): 113-24.

[57] Kukal SS, Bawa SS. Soil organic carbon stock and fractions in relation to land use and soil depth in the degraded Shiwaliks hills of lower Himalayas. Land Degradation & Development. 2014 Sep; 25 (5): 407-16.

[58] Wells T, Hancock GR, Dever C, Murphy D. Prediction of vertical soil organic carbon profiles using soil properties and environmental tracer data at an untilled site. Geoderma. 2012 Jan 15; 170: 337-46.

[59] Pauli N, Barrios E, Conacher AJ, Oberthür T. Farmer knowledge of the relationships among soil macrofauna, soil quality and tree species in a smallholder agroforestry system of western Honduras. Geoderma. 2012 Nov 1; 189: 186-98.

[60] Fontaine S, Barot S, Barré P, Bdioui N, Mary B, Rumpel C. Stability of organic carbon in deep soil layers controlled by fresh carbon supply. Nature. 2007 Nov; 450 (7167): 277-80.

[61] Luyssaert S, Schulze E, Börner A, Knohl A, Hessenmöller D, Law BE, Ciais P, Grace J. Old-growth forests as global carbon sinks. Nature. 2008 Sep; 455 (7210): 213-5.

[62] De Beenhouwer M, Geeraert L, Mertens J, Van Geel M, Aerts R, Vanderhaegen K, Honnay O. Biodiversity and carbon storage co-benefits of coffee agroforestry across a gradient of increasing management intensity in the SW Ethiopian highlands. Agriculture, Ecosystems & Environment. 2016 Apr 15; 222: 193-9.

[63] Chambers JQ, Higuchi N, Schimel JP, Ferreira LV, Melack JM. Decomposition and carbon cycling of dead trees in tropical forests of the central Amazon. Oecologia. 2000 Feb; 122 (3): 380-8.

[64] Dutta J, Banerjee K, Agarwal S, Mitra A. Soil Organic Carbon (Soc): A Proxy to Assess the Degree of Anthropogenic and Natural Stress. The Journal of Interrupted Studies. 2019 Jun 14; 2 (1): 90-102.

[65] Hertel D, Harteveld MA, Leuschner C. Conversion of a tropical forest into agroforest alters the fine root-related carbon flux to the soil. Soil Biology and Biochemistry. 2009 Mar 1; 41 (3): 481-90.

[66] Kessler M, Hertel D, Jungkunst HF, Kluge J, Abrahamczyk S, Bos M, Buchori D, Gerold G, Gradstein SR, Köhler S, Leuschner C. Can joint carbon and biodiversity management in tropical agroforestry landscapes be optimized?