

Research Article

Woody Species Composition, Structure, and Carbon Stock of Coffee-Based Agroforestry System along an Elevation Gradient in the Moist Mid-Highlands of Southern Ethiopia

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There is a limited effort in Ethiopia to study scientifically the ecological features of traditional coffee-based agroforestry systems. This study was initiated to determine the structure, composition, and carbon stock of woody species along an elevation gradient of a traditional coffee-based agroforestry system in Yirgacheffe district, southern Ethiopia. Woody plants' inventory was conducted in thirty-eight sampling quadrats (20 * 20 m) along five elevation contours and eight transects. Thirty-eight soil samples were taken from randomly selected subplots at 0–30 cm soil depths. In this study 32, woody plant species representing 23 families were recorded. Species richness ranged from 13–17 along the elevation gradient. Woody plant diversity indices appear to have a slight variation with increasing elevation gradient. Shade tree and coffee shrub density, DBH, and height showed significant variations along the elevation gradient. Total aboveground woody biomass carbon stock along elevation gradient ranged from 11.07 to 27.48 Mg·ha⁻¹. Soil organic carbon stock was slightly different across elevation gradients with a mean range of 83.91 to 89.29 Mg·ha⁻¹. These indicate that the agroforestry system has significant potential of storing and enhancing ecosystem carbon stocks across all the elevation gradients. The findings generally show that agroforestry systems in the study area are diverse, structurally complex with significant carbon storage in the soil and woody biomass.

1. Introduction

For many centuries, agroforestry has been and is a predominant subsistence farming practice throughout the globe [1]. Perhaps, in the Ethiopian farming system, agroforestry is as old as agriculture itself [2, 3]. It is believed that moist montane forest ecosystem areas of the country have historically evolved into different managed coffee production systems, which vary in terms of management intensity, structural complexity, and product diversity [4]. Coffee-based agroforestry system is among the most structurally complex and diverse forms of agroforestry systems practiced for centuries in Ethiopia [4–6]. Its upper strata are dominated by overstory shade trees (fruit and timber trees) and commonly managed in association with other perennial

crops such as coffee (*Coffea arabica* L.) and enset (*Ensete ventricosum*) and annuals that form a seemingly unbroken vegetation cover [3–5, 7–10].

Coffee-based agroforestry system provides several ecosystem benefits. The system has been recognized for its potential for forest conservation and biodiversity protection [11, 12]. Of the ecological benefits from such a system, one is shade-grown coffee [13] and its capacity to adapt coffee production to future climate change [11]. *Cordia africana*, *Albizia gummifera*, and *Millettia ferruginea* are some of the common shade trees for coffee growing on homesteads in Wondo Genet site, a sub-humid tropical region in southern Ethiopia [14]. Due to the natural forest-like structure and floristic characteristics, coffee agroforestry is often regarded as more compatible with the conservation of ecosystem

integrity [9,15]. [16] have shown that shaded systems offer great potential to reconcile biodiversity conservation and local development. A study conducted in southwestern Ethiopia by [17] indicated that traditional shade coffee management practices can maintain a diverse suite of forest birds. In addition to the ecosystem benefits, agroforestry can contribute to food security [18] and income and a wide range of other products such as fuelwood, construction material, fodder, spices, and medicinal plants [19]. It is seen as a multidimensional system with biophysical and socioeconomic components.

In respect to global climate change, agroforestry systems can present a unique opportunity to sequester large amounts of atmospheric carbon dioxide and increase carbon stocks in the aboveground as well as belowground [20,21]. [22] have shown that coffee agroforestry systems have the potential to sequester more SOC than coffee monoculture in Uganda. A study by [7] in southwestern Ethiopia also revealed that the coffee-based agroforestry systems stock significantly higher total carbon than the home garden agroforestry system. Coffee agroforestry systems can moderate high-temperature extremes and is resistant to expected near-future temperature increases resulting from climate change [11]. Thus, agroforestry is a key approach and a promising strategy in the integration of climate change adaptation and mitigation objectives, often generating significant co-benefits for local ecosystems and biodiversity [23,24]. According to an estimate by [25], the mitigation potential from agroforestry ranges between 0.08 and 5.7 Gt CO₂ yr⁻¹.

The impact of any agroforestry system on atmospheric carbon sequestration and soil organic carbon (SOC) stock depends largely on the amount and quality of biomass input, non-tree components of the system, and soil properties [20]. The SOC concentration and pools are higher in soils under agroforestry and increased with stand age [26]. Higher species richness and tree density can result in potentially higher SOC contents and increases in fine root productivity in agroforestry systems. Next to natural forests, agroforestry systems are more efficient at sequestering carbon than annual cropping systems [20,27]. The establishment of coffee agroforestry can cause SOC stocks to rebound to near forest levels [28]. Therefore, a coffee-based agroforestry system may present an attractive opportunity for coffee growers to benefit economically if the carbon sequestered is sold through carbon trading. Hence, coffee agroforestry systems are being considered as a climate change mitigation option through carbon sequestration [22].

In the south-eastern escarpment of Ethiopia, a coffee-based agroforestry system is a common practice [29]. Particularly, the traditional coffee-based agroforestry system of Yirgacheffe district is internationally famous for its high-quality and being organic coffee (*Coffea arabica* L.). Structural complexity and diversity of plant species are common features of coffee-based agroforestry systems in the southern part of Ethiopia [4,6]. The structural complexity of such systems varies, ranging from complex and diverse forms containing numerous species and strata to less complex forms, with one or two crop/tree mixtures [30,31]. Shade tree in these systems provides several benefits to coffee

plants such as microclimate modifications, improving bean characteristics, suppression of weeds [31], buffering of humidity and soil moisture availability, and improvement of soil fertility including erosion reduction [32].

Understanding the current status of the woody species structure of the traditional coffee-based agroforestry system is crucially important for the improvement of traditional systems [33], to solve the controversy regarding the value of the systems for conservation of biodiversity and ecosystem service conservation [10,15]. If agroforestry is to be used in carbon sequestration schemes, better information is required in several areas. As an option for maintaining native woody species, more attention should be given to recognition of the indigenous agroforestry systems [34].

Previous studies on coffee-based agroforestry in Ethiopia were mainly focused on assessing and comparison of woody species with other adjacent farming systems [6,35] and management and productivity of the coffee plants [36]. Studies to understand biomass and SOC stock under coffee-based agroforestry systems is limited. Except in southwest highlands Ethiopian [37], the woody species structures and composition of the coffee-based agroforestry system along an elevation gradient are largely unexplored scientifically. Especially, little is known about the contributions of the internationally famous high-quality organic coffee producing area Yirgacheffe coffee-based agroforestry to carbon stock both in biomass and soil. Despite the number of studies, most studies lack integrating several issues i.e., assessing woody species diversity with carbon stock in one complete study. Indeed, it is known that species diversity and composition of coffee-based agroforestry are influenced by ecological and cultural factors [30] as well as elevation gradients [4,32]. Therefore, this study was aimed to determine the diversity of woody species and to quantify biomass and SOC stock in the traditional coffee-based agroforestry system of the Yirgacheffe district in southern Ethiopia.

2. Materials and Methods

2.1. Description of the Study Site. The study was carried out in the Yirgacheffe district of the Southern Nations Nationalities and Peoples Regional State, Ethiopia. It is located 397 km south of Addis Ababa within the Central Rift Valley eastern escarpment between geographical coordinates of 6°5'8" to 6°19'27" N and 38°4'48" to 38°19'12" E (Figure 1). The elevation of the district ranges from 1600 to 2853 m a.s.l. The area receives a mean annual rainfall ranging from 1500 to 1700 mm with a bio-modal pattern. The mean monthly temperature is 19°C with mean monthly minimum and maximum temperatures of 16 and 28°C, respectively. The district has a moist mid-highlands climate type [38] (Figure 2). Eutric Leptosols cover the majority area of the district. These soils are derived from the flood basal with minor salic flows of Jimma Volcanics [40]. The district covers a total area of 303.91 km². Over 65% of the district land is covered by a coffee-based agroforestry system. Yirgacheffe district has a total population of 246,573. Out of these, 13% are urban and 87% are rural settlers [41]. The population density of the district is one of the highest in the country which is reported to be 811.33 persons per km².

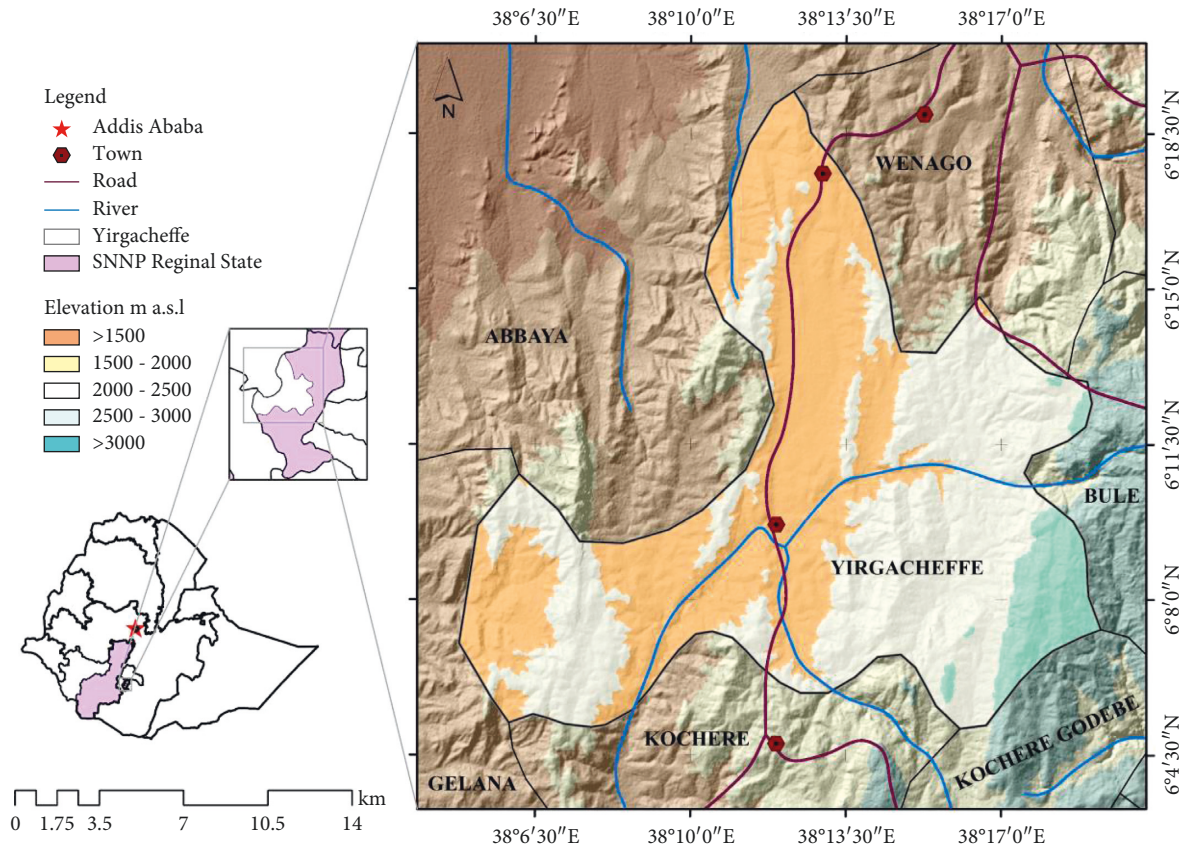


FIGURE 1: Location map of the study district.

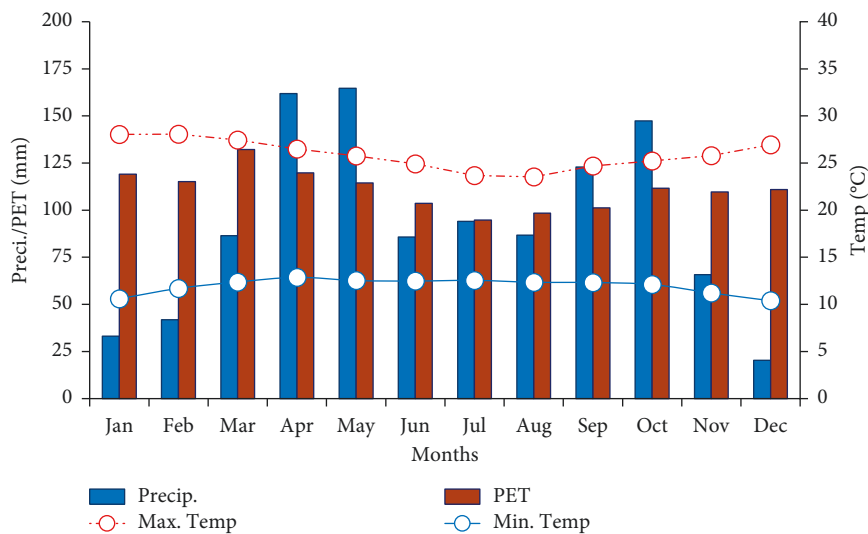


FIGURE 2: Monthly average precipitation (mm) and monthly maximum, minimum, and average temperature (°C) [39].

2.2. Sampling and Data Collection Design

2.2.1. Woody Vegetation. In the Yirgacheffe district, an area predominantly covered by coffee-based agroforestry with an elevation gradient that represents the largest possible local variations was systematically selected. The site was divided into five elevation contours that have 100 m vertical

differences (1840, 1940, 2040, 2140, and 2240 m a.s.l.). Then, across the selected elevation gradients, eight transect lines apart 500 m each other were laid [42]. In total, thirty-eight sampling quadrats were located at each intersecting point of contour and transect lines. Vegetation data for woody species >5 cm dbh were recorded on 20 × 20 m size quadrat plots. Inside the main quadrats, one 5 × 5 m nested subplot

was randomly laid out to collect data on coffee shrub parameters and smaller plants (saplings and seedlings) < 5 cm dbh [43, 44]. Plant species identification was done using [45–51].

2.2.2. Soil. Soil samples at each gradient were collected using auger from the 5 * 5 m subplots in four corners and one at the middle and mixed in to form one composite soil sample. A total of 38 soil samples were collected from the 0–30 cm soil depths [52]. Approximately 1 kg of composite sample was brought to a soil laboratory for chemical analysis. Additional undisturbed soil was sampled using a cylindrical core from 0 to 30 cm depth for the determination of bulk density. Soil samples were air-dried at room temperature and passed through a 2-mm sieve for chemical analysis.

2.3. Data Analysis. The similarity of communities of woody species across along elevation gradient was calculated using the Sørensen's similarity index [53]:

$$C_s = \frac{2a}{2a + b + c} * 100, \quad (1)$$

where, a = is the number of woody species common to both elevation gradients, b = is the number of woody species on an elevation gradient 1 only, and c = is the number of woody species on an elevation gradient 2 only. To compare woody species composition among elevation gradients, species richness, Shannon-Wiener diversity (H') index, and Shannon evenness measure (E') indices were analyzed. Shannon-Wiener diversity (H') index was calculated using [53]:

$$H' = - \sum_{i=1}^s p_i \ln p_i, \quad (2)$$

where H' is a Shannon-Wiener (H') diversity index, P_i = is the proportion of individual woody species found in the quadrats, S = the number of woody species, and \ln = natural logarithm. Evenness refers to the variability in the relative abundance of woody species. The evenness index describes the equality of woody species abundance in a community. Evenness (E') was calculated using the following equation [43, 53]:

$$J = \frac{H'}{H_{\max}} = \frac{- \sum_{i=1}^s p_i \ln p_i}{\ln S}, \quad (3)$$

Woody species structure was determined using quantitative analysis parameters such as mean diameter and mean height distribution, density (number of trees ha^{-1}), and basal area ($\text{m}^2 \cdot \text{ha}^{-1}$). Basal area (BA) is the cross-sectional area of a tree estimated at breast height (1.3 m), which is expressed in m^2 . Basal area was calculated using the following formula [42]:

$$g = \frac{\pi d^2}{4}, \quad (4)$$

where, g = is a basal area (m^2) and d = is the diameter at breast height of a tree. Importance value index (IVI) is used as a measure of woody species composition that combines frequency, abundance, and dominance importance values. The ecological importance of woody species (IVI) was determined using relative density, relative frequency, and relative dominance parameters [43].

$$\text{Relative abundant (RA)} = \frac{\text{Number of individuals of a species}}{\text{Total number of Individuals}} \times 100, \quad (5)$$

$$\text{Relative dominance (RD)} = \frac{\text{Dominance* of a species}}{\text{Dominance of all species}} \times 100, \quad (6)$$

$$\text{Relative frequency (RF)} = \frac{\text{Frequency of a species}}{\text{Frequency of all species}} \times 100, \quad (7)$$

$IVI \text{ of each species} = RA + RD + RF$ (equation (8)). Where dominance is defined as the mean basal area per tree, multiplied by the number of trees of the species.

2.3.1. Aboveground Woody Biomass and Carbon Stock Estimation. This study used two allometric models to estimate the aboveground biomass of woody species. Other than *Coffea arabica* L. and a few other woody species, the lower strata of the coffee agroforestry system are less covered by shrub (short) woody species. The dominant woody species in the coffee agroforestry systems are taller shade trees (>5 m height) which make up the upper strata of the system. This is due to coffee management practice; only important shade tree species are kept in the system. Other

woody species which are not useful in the coffee agroforestry system are systematically removed. Due to the tree management practices i.e., lopping and pollarding, the natural vegetation architecture in the coffee agroforestry system is modified [5]. Even though, there are several site-specific general multispecies allometric equations developed for woody species in a different part of Ethiopia, the vegetation structure (maybe dominantly covered by shrub species) in these systems is different from coffee agroforestry systems. Thus, except for coffee shrub, for the rest of the woody species in this study, a multispecies allometric equation that was used by Steffan-Dewenter et al. [54] for the coffee agroforestry system in the subtropical humid forest type was used.

$$\ln Y = -3.375 + 0.948 * \ln(\text{db h}^2 * H), \quad (9)$$

To estimate the aboveground biomass of coffee shrub, an allometric equation developed by [55] for the nearby coffee agroforestry system of southern Ethiopia was used.

$$Y = 0.281D^{2.06}, \quad (8)$$

where Y = biomass coffee shrub⁻¹ (kg) and D = diameter at stump height.

Then, tree biomass was converted into C by multiplying the aboveground tree/shrub biomass by 0.5 [56]:

$$\text{Above Ground Biomass C stock} = Y * 0.5, \quad (11)$$

where Y = biomass tree⁻¹ (kg).

Total woody biomass carbon stock was calculated on a hectare basis.

2.3.2. Soil Analysis and Soil Organic Carbon Stock Determination. Bulk density was determined by the core method [57]. Soil organic carbon was determined following the Walkley-Black oxidation method [58]. Then, soil organic carbon (SOC) stock for each sampled depth was calculated using the following equation (52):

$$\text{SOC stock (MgCha}^{-1}\text{)} = \text{OC} * d * \text{Bd} * 10, \quad (12)$$

where OC = organic carbon concentration (g C (kg soil)⁻¹) determined in the laboratory, Bd = bulk density (Mg m⁻³), d = soil depth (m), 10 is used to convert units to Mg C ha⁻¹.

2.4. Statistical Analysis. Both vegetation and SOC stock data were treated using one-way analysis of variance (ANOVA) following linear model (GLM) procedure. If statistical significance differences were observed ($p < 0.05$), post hoc test of Tukey's honest significant difference (HSD) test was used to separate the means. All statistical analyses were performed using SAS 9.2 statistical software (SAS Institute Inc. 2009).

3. Results

3.1. Floristic Composition and Diversity. A total of 32 woody plant species representing 23 families were recorded in 38 quadrats. From the total woody species recorded, 39%, 11%, 50% were trees, seedlings, and saplings and shrubs (including coffee shrubs), respectively. The highest similarity of woody plant species was observed between the adjacent elevation gradients, whereas, the lowest was recorded between 2040 and 2240 and 1840 and 2140 m a.s.l (Table 1). *Albizia gummifera*, *Coffea arabica*, *Croton macrostachyus*, *Eucalyptus camaldulensis*, *Millettia ferruginea*, and *Vernonia amygdalina* were woody plant species which existed across all elevation gradient. Five woody plant species (*Aningeria adolfi-friederici*, *Galiniera coffeoides*, *Lepidotrachelia*, *Podocarpus falcatus*, and *Spathodea nilotica*) were only recorded in the lower elevation gradient (1840 m). Except at 1840 and 2040 m, only two woody plant species which solely existed per each elevation gradient were recorded. Native and exotic species were accounting for 87.5 and 12.5%, respectively. At lower (1840 m) *Eucalyptus camaldulensis* and *Persea americana* were dominant, whereas in the upper (2140 m)

TABLE 1: Sørensen's similarity index (%) of species along elevation gradients of coffee-based agroforestry system.

Elevation gradient (m a.s.l)	1840	1940	2040	2140	2240
1840	100				
1940	60	100			
2040	53	79	100		
2140	48	65	65	100	
2240	59	52	38	67	100

Juniperus procera, *Millettia ferruginea*, and *Erythrina abyssinica* were dominant. Out of all woody species recorded, 44.44% and 29.63% of the total woody species were recorded at 2040 m and 1840 and 1940 m, respectively.

In the study area, woody species richness does not show any significant difference along elevation gradients ($p < 0.05$) (Table 2). Despite the significance of woody plant species richness per plot, it ranged from 13 to 17 across the elevation gradient. Shannon-Wiener index, evenness, and Simpson index did not vary significantly across elevation gradients ($p < 0.05$). The mean Shannon-Wiener index (H') of woody species for the coffee-based agroforestry system ranged from 1.00 per plot (2240 m) to 1.29 per plot (2140 m) (Table 2). Evenness of woody plant species shows a trend of increase with increasing elevation gradient.

3.2. Woody Species Structure. Mean shade trees and coffee shrub dbh, height, and density per hectare were significantly ($p < 0.05$) different along elevation gradients (Table 3). The highest shade tree density (2213 ha⁻¹) was recorded at the upper elevation gradient (2240 m), and the smallest density (631 ha⁻¹) was observed at the lower elevation gradients (2040 m). Statistically, both the higher (4160 ha⁻¹) and the lowest (2313 ha⁻¹) coffee shrub density was recorded at the lower elevation gradient 1940 and 1840 m, respectively. The difference in the mean basal area of shade trees and coffee shrub across the elevation gradients was not statistically significant ($p < 0.05$). The mean basal area of coffee shrub was higher (9.77 m²·ha⁻¹) at 2240 m and lower at 2140 m (3.37 m²·ha⁻¹) (Table 3).

The distribution of population structure of woody species (shade tree) and coffee shrub resembles an inverted J-shape, in which, there are a high number of individuals in the lower diameter classes but decreases towards the higher classes (Figure 3). The patterns of height class distribution of the woody species reveal a high proportion of individuals in the lowest height class and few individuals in the largest height class (Figure 3).

The most frequent woody species (shade tree) in the study site were *Coffea arabica*, *Millettia ferruginea*, *Vernonia amygdalina*, and *Croton macrostachyus* with a frequency of 18.41, 15.92, 10.95, and 10.45%, respectively. Nearly 90% of the total abundance was contributed by 53% of the total number of woody species (Table 3). Importance value indices revealed that *Coffea arabica* (145.09%), *Millettia ferruginea* (41.12%), *Vernonia amygdalina* (21.20%), *Croton macrostachyus* (14.45%), and *Eucalyptus camaldulensis* (12.28%) were structurally the most important species

TABLE 2: Mean value of woody species richness, Shannon-Wiener index, evenness, and Simpson index along an elevation gradient of coffee-based agroforestry system.

Elevation gradient (m a.s.l)	Richness plot ⁻¹	Total no species	Shannon plot ⁻¹	Simpson plot ⁻¹	Evenness plot ⁻¹
1840	5.50 ± 0.82	16	1.25 ± 0.13	0.66 ± 0.06	0.77 ± 0.05
1940	5.63 ± 0.91	16	1.22 ± 0.15	0.69 ± 0.04	0.74 ± 0.04
2040	4.75 ± 0.82	13	1.27 ± 0.08	0.64 ± 0.03	0.77 ± 0.03
2140	5.00 ± 1.18	17	1.29 ± 0.16	0.65 ± 0.07	0.80 ± 0.05
2240	3.88 ± 0.52	13	1.00 ± 0.11	0.63 ± 0.03	0.80 ± 0.04
<i>p</i> - value	0.64		0.54	0.65	0.84

Means ± S.E. with different letters within a column are significantly different ($p < 0.05$) (Tukey's test HSD). S.E = standard error.

TABLE 3: Mean value of woody species dbh, height, density, and basal area along an elevation gradient of coffee-based agroforestry system.

Elevation gradient (m a.s.l)	dbh (cm)		Height (m)		Density ha ⁻¹		Basal area m ² ha ⁻¹	
	Shade trees	Coffee shrub	Shade trees	Coffee shrub	Shade trees	Coffee shrub	Shade trees	Coffee shrub
1840	13.64 ± 1.34 ^{ab}	7.16 ± 0.79 ^{ab}	15.33 ± 1.53 ^{ab}	3.55 ± 0.18 ^{ab}	790.63 ± 384.38 ^b	2313.13 ± 183.59 ^b	7.52 ± 2.97	7.04 ± 0.81
1940	12.73 ± 1.47 ^b	5.45 ± 0.51 ^{bc}	13.13 ± 1.82 ^{ab}	2.96 ± 0.08 ^b	780.75 ± 219.80 ^b	4160.00 ± 473.77 ^a	5.44 ± 2.18	7.30 ± 2.07
2040	14.23 ± 1.24 ^{ab}	4.93 ± 0.31 ^{bc}	12.57 ± 1.13 ^{ab}	2.83 ± 0.07 ^b	631.63 ± 152.08 ^b	3664.25 ± 495.94 ^{ab}	6.23 ± 1.39	7.16 ± 1.40
2140	12.31 ± 2.04 ^b	4.22 ± 0.38 ^c	10.78 ± 1.22 ^b	3.07 ± 0.22 ^b	1183.25 ± 284.32 ^{ab}	2604.00 ± 465.14 ^{ab}	4.78 ± 1.65	3.37 ± 1.30
2240	19.69 ± 1.80 ^a	8.18 ± 0.85 ^a	17.75 ± 1.52 ^a	3.82 ± 0.27 ^a	2213.25 ± 542.16 ^a	2823.63 ± 447.03 ^{ab}	8.54 ± 1.65	9.77 ± 2.19
<i>p</i> - value	0.02	<0.00	0.02	<0.01	0.02	0.02	0.69	0.16

Means ± S.E. with different letters within a column are significantly different ($p < 0.05$) (Tukey's test HSD). S.E = standard error.

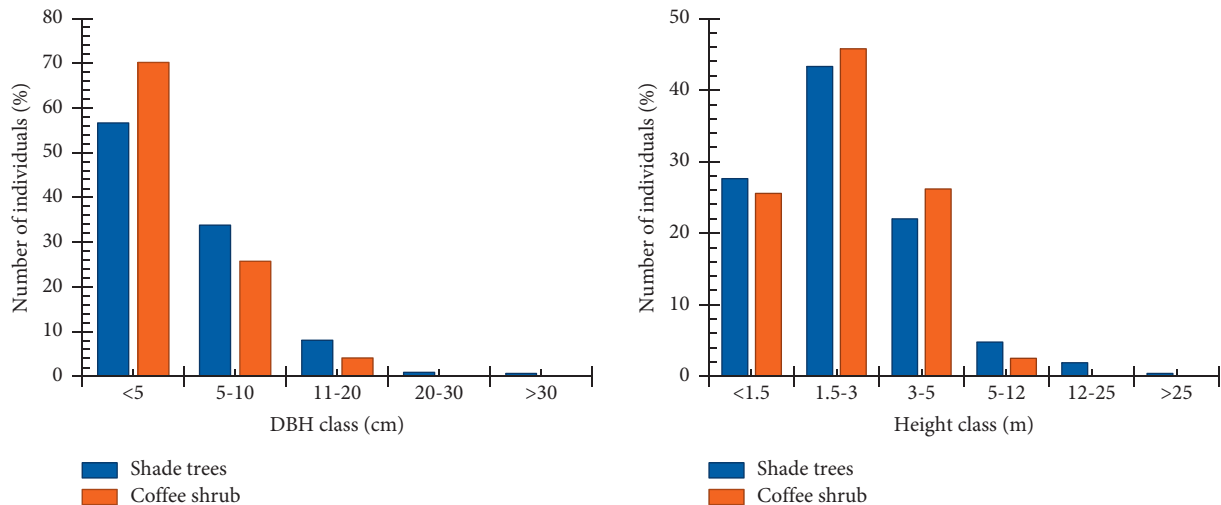


FIGURE 3: Diameter (DBH) and height class distribution of shade tree species and coffee shrub in coffee-based agroforestry system.

(Table 4). Throughout the coffee-based agroforestry system *Vernonia amygdalina*, *Millettia ferruginea*, and *Cordia africana* were the shade tree species that have the highest density (307, 299, and 165 tree ha⁻¹, respectively) (Table 4).

3.2.1. Carbon Stock in Aboveground Biomass of Woody Species and Soil Organic Carbon. In the traditional coffee-based agroforestry system AGB of shade trees showed a significant ($p < 0.05$) difference along the elevation gradient, whereas AGB of coffee shrub did not vary significantly ($p < 0.05$) (Table 5). The highest (34.24 Mg ha⁻¹) and the lowest (14.10 Mg ha⁻¹) shade trees AGB was found at the

2240 and 2140 m, respectively. Aboveground biomass of coffee shrub ranges from 20.72 Mg ha⁻¹ at the 2240 m to 8.05 Mg ha⁻¹ at the 2140 m. Coffee shrub alone contributes over 41% to the total AGB coffee-based agroforestry system. Significance ($p < 0.05$) differences in total AGB and BGB were also observed along the elevation gradient of the coffee-based agroforestry system. The difference in soil bulk density along the elevation gradient was significant ($p < 0.05$). Similarly, soil organic carbon also showed a significant difference across the elevation gradient of the coffee-based agroforestry system (Table 5).

Means ± S.E. with different letters within a column are significantly different ($p < 0.05$) (Tukey's test HSD).

TABLE 4: Mean value of woody species density, RF, RA, RD, and IVI along an elevation gradient of coffee-based agroforestry system.

Scientific name	Family	Density(ha ⁻¹)	RF%	RA%	RD%	IVI
<i>Coffea arabica</i> L.	Rubiaceae	3251	18.41	75.76	50.92	145.09
<i>Millettia ferruginea</i> (Hochst.) Bak.,	Fabaceae	299	15.92	6.96	18.24	41.12
<i>Vernonia amygdalina</i> Del.	Asteraceae	307	10.95	7.15	3.10	21.20
<i>Croton macrostachyus</i> Hochst. Ex Engl.	Eupborbiaceae	34	10.45	0.79	3.21	14.45
<i>Eucalyptus camaldulensis</i> Dehnh.*	Myrtaceae	42	6.47	0.97	5.37	12.81
<i>Cordia africana</i> Lam.,	Boraginaceae	165	5.47	3.84	2.96	12.28
<i>Erythrina abyssinica</i> Lam. ex DC.,	Fabaceae	6	3.98	0.13	1.63	5.75
<i>Persea americana</i> Mill, *	Lauraceae	8	2.99	0.19	2.08	5.26
<i>Dracaena steudneri</i> Engler,	Dracaenaceae	3	1.49	0.06	2.91	4.46
<i>Albizia gummifera</i> (I. F. Gmel.) C.A. Sm.	Fabaceae	14	3.48	0.33	0.45	4.26
<i>Polyscias Fulva</i> (Hiem) Harms	Araliaceae	16	2.99	0.37	0.85	4.21
<i>Juniperus procera</i> Hoches. Ex. Endl	Cupressaceae	15	1.49	0.34	2.29	4.13
<i>Rhamnus prinoides</i> L'Herit.,	Rhamnaceae	53	1.99	1.22	0.52	3.74
Unidentified		33	2.49	0.76	0.20	3.44
<i>Afrocarpus falcatus</i> (thum) Mirb	Podocarpaceae	1	0.50	0.03	2.68	3.20
<i>Prunus africana</i> (Hook. f.) Kalkm*	Rosaceae	2	1.49	0.04	0.67	2.20
<i>Strychnos spinosa</i> Lam., Subsp. <i>Lokua</i> (A. Rich)	Loganiaceae	3	1.49	0.06	0.58	2.14
<i>Fagaropsis angolensis</i> (Engl.) Dale,	Rutaceae	4	1.00	0.09	0.33	1.42
<i>Ficus sur</i> Forssk.	Moraceae	1	1.00	0.03	0.14	1.17
<i>Lannea schimperi</i> (A. Rich.) Engl.,	Anacardiaceae	1	1.00	0.03	0.00	1.03
<i>Aningeria adolfi-friederici</i> (Engl.) Robyns & Gilbert.	Sapotaceae	1	0.50	0.01	0.51	1.02
<i>Maytenus</i> spp.	Celastraceae	10	0.50	0.24	0.01	0.75
<i>Brucea antidysenterica</i> J.F. Mill.,	Simaroubaceae	10	0.50	0.24	0.01	0.74
<i>Catha edulis</i> (Vahl) Forssk. ex Endl.,	Celastraceae	10	0.50	0.24	0.01	0.74
<i>Apodytes dimidiata</i> E. Mey. Ex Am.,	Icacinaceae	1	0.50	0.01	0.10	0.61
<i>Spathodea nilotica</i> Seem.,	Bignoniaceae	1	0.50	0.01	0.08	0.59
<i>Pronus persica</i> (L.) Batsch,	Rosaceae	1	0.50	0.01	0.06	0.57
<i>Lepidotrachelia volkensii</i> (Gürke) Leroy,	Meliaceae	1	0.50	0.01	0.05	0.56
<i>Galiniera coffeoides</i> Del.	Rubiaceae	1	0.50	0.01	0.02	0.53
<i>Ekebergia capensis</i> Sparrm.	Meliaceae	1	0.50	0.01	0.01	0.53
Total		4292	100	100	100	300

Means \pm S.E. with different letters within a column are significantly different ($p < 0.05$).

(Tukey's Test HSD). RF = Relative Frequency, RA = Relative Abundant, RD = Relative Dominance, IVI = Importance Value Index, And * = Exotic Species

TABLE 5: Mean value of woody species AGB (Mg ha⁻¹), BGB (Mg ha⁻¹), soil bulk density (g cm⁻³), and SOC % along an elevation gradient of coffee-based agroforestry system.

Elevation gradient (m a.s.l)	Shade trees AGB	Coffee shrub AGB	Total AGB	BGB	Bulk density	SOC
1840	18.39 \pm 3.85 ^{ab}	16.16 \pm 3.76	34.55 \pm 4.58 ^{ab}	8.64 \pm 1.15 ^{ab}	0.80 \pm 0.02 ^b	3.58 \pm 0.17 ^{ab}
1940	17.42 \pm 5.50 ^{ab}	14.39 \pm 2.87	31.81 \pm 4.92 ^b	7.95 \pm 1.23 ^b	0.89 \pm 0.02 ^a	3.26 \pm 0.20 ^{ab}
2040	22.99 \pm 4.66 ^{ab}	15.13 \pm 3.30	38.12 \pm 6.85 ^a	9.53 \pm 1.71 ^a	0.92 \pm 0.01 ^a	3.05 \pm 0.21 ^b
2140	14.10 \pm 4.18 ^b	8.05 \pm 2.89	22.14 \pm 4.27 ^b	5.54 \pm 1.07 ^b	0.75 \pm 0.02 ^c	3.72 \pm 0.16 ^a
2240	34.24 \pm 4.22 ^a	20.72 \pm 4.15	54.96 \pm 6.17 ^a	13.74 \pm 1.54 ^a	0.84 \pm 0.03 ^{ab}	3.53 \pm 0.22 ^{ab}
<i>p</i> -value	0.03	0.16	<0.00	<0.00	<0.00	0.02

S.E = standard error, AGB = aboveground biomass, BGB = below ground biomass, and SOC = soil organic carbon.

Mean total AGB carbon stock of shade trees significantly varied from 27.48 Mg ha⁻¹ at 2240 m to 11.07 Mg ha⁻¹ at 2140 m. The mean BGB carbon stock followed a similar trend to the total AGB carbon stock. It was significantly higher (6.87 Mg ha⁻¹) at 2240 m and lower (2.77 Mg ha⁻¹) at 2140 m (Table 6). However, SOC stock did not show any significance ($p > 0.05$) difference along an elevation gradient. The total carbon stock in the coffee-based agroforestry system ranged from 123.6 Mg·ha⁻¹ at 2240 m to 97.75 Mg·ha⁻¹ at 2140 m (Table 6). The contribution of AGB

carbon, BGB carbon, and SOC (30 cm soil depth) to the total AGB carbon stock of the coffee-based agroforestry system was 16.74, 4.19, and 79.07%, respectively. Yirgacheffe traditional coffee-based agroforestry system stocks a total of 108.45 Mg C ha⁻¹ in its aboveground biomass and soil.

4. Discussion

4.1. Woody Species Composition and Diversity. The evidence from this study suggests that the traditional coffee-based agroforestry system of Yirgacheffe supports a high density of woody species. Floristic similarity (Table 1) and the existence of cash crop tree (*Coffea arabica*), legumes tree (*Millettia*

TABLE 6: Mean value of woody species AGB carbon stock (Mg ha^{-1}), BGB carbon stock (Mg ha^{-1}), SOC stock (Mg ha^{-1}), and total carbon stock (Mg ha^{-1}) along an elevation gradient of coffee-based agroforestry system.

Elevation gradient (m a.s.l.)	AGB Carbon stock	BGB Carbon stock	SOC stock	Total carbon stock
1840	$17.28 \pm 2.29^{\text{ab}}$	$4.32 \pm 0.57^{\text{ab}}$	85.71 ± 3.53	107.30 ± 5.63
1940	$15.91 \pm 2.46^{\text{b}}$	$3.98 \pm 0.61^{\text{b}}$	86.67 ± 3.15	106.55 ± 3.91
2040	$19.06 \pm 3.42^{\text{ab}}$	$4.77 \pm 0.86^{\text{ab}}$	83.19 ± 4.15	107.02 ± 7.21
2140	$11.07 \pm 2.13^{\text{b}}$	$2.77 \pm 0.53^{\text{b}}$	83.91 ± 5.03	97.75 ± 6.82
2240	$27.48 \pm 3.09^{\text{a}}$	$6.87 \pm 0.77^{\text{a}}$	89.29 ± 4.99	123.64 ± 6.38
p - value	<0.00	<0.00	0.85	0.07

Means \pm S.E. with different letters within a column are significantly different ($p < 0.05$) (Tukey's test HSD). S.E = standard error, AGB = aboveground biomass, BGB = below ground biomass, and SOC = soil organic carbon.

ferruginea), timber tree (*Cordia africana*), and fuelwood tree (*Vernonia amygdaline*) across elevation gradient indicated the coffee-based agroforestry system offers more niche for indigenous tree species. A similar result was also reported by [59] in southwestern Ethiopia. The dominance of *Eucalyptus camaldulensis* and *Persea americana* at the lower elevation gradient could be due to the species better adaptability to the gradient as well as their vigorous growth character and the difficulties in the growth of indigenous tree species [30, 60, 61]. This depicts that at the lower elevation gradients, some indigenous shade trees are being replaced by exotic tree species. Furthermore, the more unique woody species at the lower elevation gradient (1840 m) than the rest of the upper gradients was probably due to the fact that the gradient is hotter which allows the growing of moist low-land vegetation.

Despite the non-significant difference of woody species richness across the elevation gradient of the coffee-based agroforestry system, the total woody species richness ranged from 13 at the upper elevation gradient (2240 m) to 16 species at the lower elevation gradients (1840 and 1940 m) (Table 2). Shannon diversity index obtained from the studied coffee-based agroforestry system was relatively high, indicating a good collection of species. Compared to a similar study in the nearby area Dilla Zuria district by Abebe [4], this study observed greater Shannon evenness value and smaller richness of woody species. The reduction in tree species richness, especially in the upper elevation gradient of coffee-based agroforestry system might be associated with the management interventions to promote coffee production [31, 62]. Selective cutting of trees for construction and fuel wood also may contribute to the changes in tree species composition and the reduction in tree species richness. A study by Legesse and Negash, [19] in the Kacha Bira district, southern Ethiopia showed that woody species preference in the agroforestry system was dependent on the compatibility with the farming system. The management interventions in semi-forest coffee systems show a strong impact on tree species composition, especially in the upper canopy [63]. Altitude is also an important terrain variable since it affects the atmospheric pressure, moisture, and temperature, which in turn influences the growth and development of plants, and the patterns in vegetation distribution [64]. The relatively lower woody species richness in the upper gradients could be also due to the variations in environmental temperature and moisture availability. A study in home gardens of southern Ethiopia has

shown a significant decrease in plant species richness with an increasing altitudinal gradient [65].

4.2. Woody Species Structure. Tree species with a greater ecological (shade) or economic value or both were found to be frequently distributed across all elevation gradients of the coffee-based agroforestry system (Table 2). Similar results were reported by [4] from a comparison of woody species diversity along an elevation gradient in Dilla Zuria district in southern Ethiopia. In Ethiopia, to improve the production of coffee, in addition to the reduction of tree density and understory vegetation, the traditional shade tree management mainly focuses on selecting species with desirable characteristics [31, 61].

The lower number of shade trees and higher number of the coffee shrub at lower elevation gradients indicate that more area is occupied by coffee shrub than the above elevation gradients. Furthermore, the lower number of shade trees in the lower elevation gradient might be due to the selective removal of shade trees to promote coffee development. Farmers in southwestern Ethiopia remove 30% of the canopy of the semi-coffee forest system to decrease the competing vegetation and to increase coffee shrub density and productivity [66]. A study in a semi-natural coffee forest of southwestern Ethiopia by Senbeta and Denich [62] indicated that tree density was reduced to promote coffee production. Selective management of some shade trees for their ecological value (i.e., *Millettia ferruginea*) [4] in the CBAFS could be an additional reason for the lower density of shade trees at the upper elevation (Table 3). At lower elevation gradients, shade trees provide a microclimate modification [31, 32] for coffee shrubs. At high elevation gradients, shade trees restrict the sensorial quality of coffee, because temperature and radiation are reduced under shade trees [67]. Due to this reason, the upper elevation gradients are dominated by timber (*Juniperus procera*) (this species has conical canopy shape which makes it to have small shade comparing to other shade trees) and legumes trees (*Millettia ferruginea* and *Erythrina abyssinica*). However, the mean tree density in the traditional coffee-based agroforestry was higher (Figure 2) than those reported for Dilla Zuria district by Abebe [4] and Jimma's southwestern Ethiopia semi-forest coffee agroecosystems by Aerts et al. [31]. Only few shade tree species with a greater economic or ecological value (shade) or both dominated the coffee-based agroforestry

system (Table 4). Generally, tree density is associated with both the management and the biophysical conditions [68].

The high abundance of coffee shrubs at the middle gradients might be due to the high abundance of legume trees and moderate canopy cover (Table 3), which can create a favorable microclimate for coffee shrubs [31], such as enhanced soil fertility by adding N through N_2 -fixation and recycling nutrients through litter-fall or biomass-transfer [69]. This indicates that a coffee-based agroforestry system has the potential of producing organic coffee shrubs at the middle elevation gradients. The mean density of coffee shrub from this study was higher than the report of Abebe [4] and smaller than the report of Aerts et al. [31] in southern and southwestern Ethiopia, respectively. The mean coffee basal area (6.65 cm^2) and height (2.65 m) (Table 3) for the traditional coffee-based agroforestry were smaller than the coffee shrub basal area and height recorded in Dilla Zuria district, southern Ethiopia [4].

The pattern of diameter class has indicated that woody species (shade trees) and coffee shrubs have a high number of seedlings with a decreasing number of stems toward the higher diameter class (Figure 3). The overall distribution pattern of diameter classes of woody species in the coffee-based agroforestry system suggests that the stands consist of woody species with relatively wider diameter classes. However, the highest densities of tree species were found at the intermediate diameter class. The patterns of height class distribution of the woody species for this study illustrated that there was a high proportion of individuals in the lowest height class and a few individuals in the largest height class (Figure 3). Four strata were observed; the first stratum <1.5 m height is mainly made up of coffee shrub seedlings, some shade trees, and shrub seedlings; the second stratum ranging from 1.6 to 12 m height is made up of coffee shrub and some small shade trees. The third stratum ranging from 13 to 24 m in height is mainly made up of shade trees such as *Millettia ferruginea* and *Croton macrostachyus*. The fourth stratum corresponds to large trees with tree height >25 m such as *Millettia ferruginea* and *Eucalyptus camaldulensis*.

4.3. Carbon Stock in Aboveground Biomass of Woody Species and Soil Organic Carbon. Estimated AGB carbon stock in the traditional coffee-based agroforestry system falls within the range estimates of [25] for several agroforestry systems. The mean AGB carbon stock at 2240 m of the coffee-based agroforestry system ($27.48 \text{ Mg}\cdot\text{ha}^{-1}$) (Table 6) was higher than the estimations of Häger [70] for coffee agroforestry systems of Costa Rica and lower than the reported by Dossa et al. [71] and Somarriba et al. [72] in shaded-coffee agroforestry system of Central American. One of the reasons for such difference in the AGB carbon stock in this study with other similar studies might be attributable to the difference in tree density and species composition. For example, several studies have reported differences in AGB carbon stock with a difference in tree density [70–72] for different coffee agroforestry systems. It could be also a result of differences in management practices, coffee agroforestry systems stand

age, site characteristics, and composition differences [73]. The use of different allometric equations between the studies might be also a reason for the variation in aboveground biomass. Allometric equations lack accuracy either because of their very location-specific or much “generalized” nature [74].

Despite the consistency, this study demonstrated a pattern of increase of total AGB carbon with increasing elevation gradient. This might have happened due to the relatively higher shade-tree and coffee-shrub basal area at 2240 m. In the western Tigray region, Northern Ethiopia a study by Gebrewahid et al. [75] revealed that higher total carbon was produced from scattered trees on farmland at upper altitudinal gradient. The BGB carbon stock in the coffee-based agroforestry system mirrored the AGB carbon stock. Such similarity is due to the fact that the BGB carbon stock is estimated from the AGB carbon stock which resulted in a mirrored result. Though, the mean value of BGB carbon stock which ranges from 2.77 to $6.87 \text{ Mg}\cdot\text{ha}^{-1}$ at 2140 m and 2240 m, respectively (Table 6), indicated that the contribution of BGB to the total carbon stock of the coffee-based agroforestry system is considerable.

Like other studies [76, 77], this study also indicated that a major portion of the total amount of carbon in the system is stored in the soil. The SOC stock under all elevation gradients of the coffee-based agroforestry system was in general higher (Table 6). The estimated SOC stock across all elevation gradients in this study was greater than the report of Häger, [70] and lesser than the report of Dossa et al. [71] for coffee agroforestry systems. Soil organic matter content increases, in time, under agroforestry systems of coffee [32]. The relative similarity of SOC stock across all the elevation gradients in the coffee-based agroforestry system may be associated with the fact that such coffee production systems prevent erosion and can contribute to maintaining SOC stock [70].

The relatively higher total carbon stocks (Table 6) in all elevation gradients of the coffee-based agroforestry system suggests the significant potential of the system to store and enhance ecosystem carbon content. [78] also indicated that agroforestry systems with higher, compared to those with lower, number of plant species, as well as higher species richness and tree density had higher SOC. Higher soil organic C content was associated with higher species richness and tree density [1]. Such investigation can provide useful information for the national process of whether a coffee-based agroforestry system should be considered to be included as an activity within the Nation’s commenced National Program on REDD+ [73]. Thus, it can be concluded that the traditional Yirgacheffe CBAFS has a good capacity for carbon storage. In addition to the significant amount of carbon stored in aboveground biomass, agroforestry systems can also store C belowground [9].

5. Conclusions

This study provides evidence on woody species structure, diversity, and carbon stock of traditional coffee-based agroforestry along the elevation gradients in Yirgacheffe

district, southern Ethiopia. Most measured woody species' structural parameters showed significant variation along an elevation gradient. The dominance of legume and timber shade tree species from the middle to the upper elevation gradients indicates that the system has the potential of producing organic coffee shrubs at the middle elevation gradients. Total carbon stock (AGB + BGB + SOC) of the coffee-based agroforestry system along an elevation gradient suggests the significant potential of these production systems to store and enhance ecosystem carbon stocks. The appreciable amount of carbon stock reported from the traditional coffee-based agroforestry investigation implies that such multi-structured and diversified agroforestry systems can play a vital role in the combat of global warming through an eco-sustainable way of atmospheric carbon sequestration. Indeed, this study indicates that such a complex coffee-based agroforestry system could be one option to address the problems of deforestation and related resources degradation for the Ethiopian highlands. The lack of allometric equations to estimate above and belowground biomass of woody species including coffee shrubs makes the determination of biomass carbon stock in the coffee-based agroforestry systems in Ethiopia difficult. It is strongly recommended to develop species-specific allometric equations for agroforestry system.

Data Availability

No additional data is available, all the required data are included in the manuscript. But, if the raw data is required, it can be accessed through email to corresponding author.

Conflicts of Interest

The authors declare no conflicts of interest.

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