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Comparison of Woody Species Diversity and Soil Organic Carbon in Coffee-Based Forests and Natural Forests in Ethiopia

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ABSTRACT

Ethiopia is the origin of coffee arabica, which grows in moist Afromontane forests. Today, the expansion of coffee production to adjacent natural forests is high. The current study aims to compare species diversity, richness, regeneration, and soil physico-chemical properties of forests without and with coffee for conservation. A result showed that Forests without coffee have better mean species richness (45.86), Shannon wiener diversity index (2.69), Evenness (0.85), and Simpson (2.94) than forests with coffee. Forests without coffee had a higher percentage of soil carbon storage (mean 147.18) than forests with coffee (Mean 120.25). Forests without coffee are better for all comparisons. Documentation of woody species will be required for both systems for immediate conservation.

INTRODUCTION

Ethiopia is located in the Horn of Africa and the birthplace of coffee arabica, which occurs beneath moist Afromontane forests. Coffee arabica is a shade-demanding shrub or small tree that requires a suitable growth environment, such as annual rainfall between 1,600 and 1,800 mm/year and average temperatures of 18 to 24°C (Senbeta & Denich, 2006; Schmitt, 2006). Coffee arabica is the main cash crop in Ethiopia, cultivated using four production systems: garden coffee, coffee forest or wild coffee, semi-coffee forest, and plantation coffee. This review mainly focused on semi-coffee forests and plantation coffee due to intensive management activities like weeding, selective thinning, and harvesting timber trees, which harm biodiversity and the soil's organic carbon (Amamo, 2014). The other two did not affect it. For example, garden coffee occurs where coffee trees are cultivated outside the demarcated forest areas, usually around farmsteads among shade trees and other crops or fruit trees (Schmitt et al., 2010). For wild coffee, no such visible management system has been applied.

Different research has been done in Ethiopia to compare coffee-based and natural forests regarding woody species diversity and soil organic carbon (Senbeta & Denich, 2006; Mengist et al., 2013; Gessese, 2018; Beyene et al., 2022). However, the existing studies on Ethiopian forests have primarily focused separately on specific components or variables within coffee-based forests or natural forests. For instance, Kewessa et al. (2019) in Bale Ecoregion, Gamachu & Jegora (2019) in Yayo forest analyzed the diversity and structure of woody species in both forests while Daka (2022) and Dinsa (2022) assessed soil organic carbon and soil bulk density in Anfilo district and Gidame Woreda respectively in both land use types. While there have been investigations into aspects such as woody species diversity, structure, and soil organic carbon levels, there is a lack of comprehensive review that integrates these variables and directly compares coffee-based and natural forests. These studies have not been summarized as one in the form of a review until now. Summarization of different studies is important to quickly identify research gaps and minimize work repetition, saving resources and time. In addition, this review provides a holistic understanding of the similarities and differences between coffee-based forests and natural forests in terms of species composition and soil physico-chemical properties in Ethiopia.

The reasons behind the selection of woody species composition, soil organic carbon, and soil bulk density. The first species composition determines the sustainability of the forest ecosystem and the environment. The second soil is the storehouse of most carbon dioxide released to the atmosphere from different sources (the burning of fossil fuels, industry, and land use change emissions) (Wang & Azam, 2024). The third natural distribution of forest tree species, growth, and biomass is governed by soil properties. Therefore, the selected components are important for ecological balances, which determine the continuity of biodiversity of a specific ecosystem (Barrios et al., 2018).

We utilized published data sources or secondary data for this review. Then, we conducted an integrative literature review using inclusion and exclusion criteria to identify suitable documents. We used Scopus sources, Web of Science, and Google search bases. The emphasis was mainly on documents that focused on the comparison of woody species diversity and soil organic carbon in coffee-based forests and natural forests in Ethiopia. Therefore, the objectives of this review are to (1) compare the composition of woody species and the regeneration of coffee-based forests and natural forests and (2) compare the soil organic carbon and bulk density of coffee-based forests and natural forests in Ethiopia.

MATERIALS AND METHODS

Methodology

PRISMA is an established set of reporting principles for systematic review and meta-analysis in biological studies. We used two techniques to get the required documents from different databases.

Search Engines

The comparison of woody species diversity and soil organic carbon in Ethiopian natural forests and coffee-based forests can be found by using search engines. Databases for English journal publications from 2013 to 2024 are examined. Since the main goal of this analysis is to provide policymakers with thorough, up-to-date information, we only used papers published during the last eleven years, starting in 2013. We utilized the following terms: moist forest, coffee-based forests, natural forests, regeneration, woody species diversity, soil physicochemical features, bulk density, and soil organic carbon. These terms were sourced from databases such as Science Direct and Google Scholar.

Inclusion and Exclusion Techniques

Specific criteria guided our review, which included the use of the English language, limiting the selection of publication types of journal articles. We only looked at publications from the aforementioned years and limited our geographic emphasis to Ethiopia. After a thorough review of the literature, 400 potential records were found. 150 were omitted at the first stage of title-based repetition checks. The second phase was reading the abstracts and summaries of the 250 records that remained, using the inclusion and exclusion criteria as a guide. Consequently, after reading the article, 180 out of 250 records were eliminated. The remaining 70 records were then evaluated in full text.

Study Sites

This review mainly focused on research done in Ethiopia's southwestern, southeastern, western, and south-central regions, which are the areas suitable for coffee growth in the country.

Data Analysis

For the meta-analysis, R software version 4.01 was used to summarize the different results of various researchers.

RESULTS AND DISCUSSION

Diversity of Woody Species

All values of the Shannon-Wiener diversity index (is the most commonly used diversity index due to it gives information statistic indices, which means it assumes all species are represented in a sample and that they are randomly sampled), species richness, evenness, and Simpson indexes of forests without and with coffee are shown in Table 1. Belete Forest had the highest Shannon Wiener diversity indexes (3.79 and 2.82) in forests without and with coffee, respectively. However, research done in the south-central highlands of Ethiopia has the lowest Shannon Wiener diversity indexes (0.4 and 0.21), respectively, in forests without and with coffee. The highest species richness was recorded in Sheko Woreda Forest for forests without and with coffee, with values of 107 and 65, respectively. Nevertheless, the lowest value registered in the Saki natural forest was for forest without coffee (19), and the species richness of forest with coffee was approximately 10 as per research done in the Gimbo district forest. The maximum value of evenness for forests without coffee was recorded in the Gimbo district (1.62). The forest with coffee had the lowest value, obtained from the result of the Saki natural forest with a value of 0.96. The highest forest values with and without coffee were recorded for Belete Forest (13.9 and 4.2), respectively. Finally, the lowest value was recorded for the forest without and with coffee in Belete Forest, with values of 0.16 and 0.45, respectively.

Table 1. Diversity and related information on forests without and with coffee

Index	Forest without coffee	Forest with coffee	Authors
Shannon Wiener diversity index	2.98	2.13	(Mengist et al., 2013)
Species richness	55	45	
Evenness	0.74	0.56	
Simpson index	13.9±0.93	4.2±0.70	
Shannon Wiener diversity index	2.15 ± 0.07	1.74 ± 0.10	(Kewessa et al., 2019)
Species richness	19 ± 0.9	12.55 ± 0.73	
Simpson index	0.84 ± 0.01	0.74 ± 0.04	
Shannon Wiener diversity index	3.07	2.13	(Gamachu & Jegora, 2019)
Species richness	54	38	
Simpson index	0.92	0.70	
Shannon Wiener diversity index	3.07	2.30	(Denu, 2019)
Species richness	19	11	
Evenness	1.0	0.96	
The density of woody species/ha	315	91	
Shannon Wiener diversity index	3.79	2.82	(Yasin et al., 2018)
Species richness	55	33	
Evenness	0.95	0.81	
Simpson Diversity Index	0.16	0.45	
Shannon Wiener diversity index	3.23	2.00	(Belay et al., 2019)
Species richness	60	48	
Evenness	0.79	0.52	
Shannon Wiener diversity index	2.79	1.84	(Gessese, 2018)
Simpson index	0.91	0.80	
Species richness	27	10	
Evenness	0.60	0.63	
Shannon Wiener diversity index	2.56(±0.24)	1.63(±0.42)	(Likassa & Gure, 2017)
Species richness	49	36	
Evenness	0.96(±0.02)	0.91(±0.07)	
Shannon Wiener diversity index	2.97	1.33	(Wood et al., 2019)
Species richness	107	65	
Evenness	0.63	0.34	

Shannon Wiener diversity index	2.72 ± 0.31	1.42 ± 0.49	(Betemariyam et al., 2023)
Simpson index	0.91 ± 0.03	0.58 ± 0.16	
Species richness	64	27	
Evenness	0.76 ± 0.10	0.49 ± 0.10	
Shannon Wiener diversity index	0.40	0.21	(Kefalew et al., 2023)
Species richness	33	24	
Evenness	0.45	0.23	

Regeneration Information of Forest without and with Coffee

From all investigated values, the highest value of seedlings was recorded for forests without and with coffee in the Bale eco-region, with values of 22,630 and 7110 per hectare, respectively. In addition, the lowest values were recorded in the Saki natural forest for both forests without and with coffee, with values of 172 and 27 per hectare, respectively (Table 2).

The highest sapling density was recorded for research done in Gidame Woreda, with a value of 3,287 per hectare for a forest without coffee. However, the lowest value of saplings was documented in the Gimbo district for the forests with coffee, with a value of 1023 per hectare. The lowest value of saplings recorded for forests without and with coffee for Tululujia Control Hunting Area Natural Forest was 94 and 5 per hectare, respectively (Table 2). For mature trees, the highest density was recorded in Gidame Woreda Forest, with a value of 740 per hectare for forests without coffee, and forests with coffee had the highest value of mature trees recorded in Belete Forest. The lowest values were recorded for both systems for Saki Natural Forest, with values of 42 and 32 per hectare, respectively (Table 2).

Table 2. Regeneration information of forest without and with coffee

	Forest without coffee	Forest with coffee	
Growth form	density/ha	density/ha	Authors
Seedlings	16000	4620	(Mengist et al., 2013)
Saplings	1337	521	
Mature trees	274	187	
Seedlings	172	27	(Denu, 2019)
Saplings	101	32	
Mature trees	42	32	
Seedlings	4583 ± 67	237 ± 7.3	(Akena, 2022)
Saplings	3287 ± 35	314 ± 73	
Mature trees	740 ± 14	344 ± 15	
Seedlings	1950	1448	(Yasin et al., 2018)
Saplings	579	424	
Mature trees	458	424	
Seedlings	53 %	41 %	(Belay et al., 2019)
Saplings	39 %	51 %	
Mature trees	8 %	8 %	
Seedlings	118	55	(Belay et al., 2019)
Saplings	94	5	
Mature trees	NA	NA	
Seedlings	22,630±1872	7110±1009	(Nigatu et al., 2017)
Saplings	658.75±109	176.25±38.75	
Mature trees	635±58.75	402.5±35.75	

Soil Organic Carbon and Bulk Density of the Forest without and with Coffee

The highest soil carbon stock potential was recorded in the Gura-Ferda natural forest, with a value of 229.83 and 178.09 per hectare for forests without and with coffee, respectively. In addition, the lowest values were recorded for both systems, with values of 51.35 and 50.64 per hectare, respectively (Table 3). The highest soil bulk density was recorded in Belete Gera Forest, with values of 0.92 and 0.82 grams per cubic centimeter, respectively, for the forest without and with coffee.

Table 3. Summary of soil organic carbon and bulk density of forests without and with coffee

Contribution of forest	Forest without coffee	Forest with coffee	Authors
Soil carbon stock potential	148.40 ± 12 t c ha^{-1}	153.80 ± 4.30tc ha^{-1}	(Dinsa, 2022)
Soil bulk density	0.78±0.05 g cm^{-3}	0.81±0.02 g cm^{-3}	
Soil carbon stock potential	170.11(±14.59) t c ha^{-1}	127.96(±9.43) t c ha^{-1}	(Mengistu & Asfaw, 2019)
Soil bulk density	NA	NA	
Soil carbon stock potential	229.83 ± 31.42 (Mg C/ ha)	178.09 ± 36.21 (Mg C/ ha)	(Betemariyam et al., 2023)
Soil bulk density	NA	NA	

NA stands for Not Available.

Results of the Meta-Analysis

Shannon diversity ratings in forests lacking coffee ranged from 0.4 to 3.79. However, diversity in the coffee-growing forest varies from 0.21 to 2.82. The two land use systems have biodiversity ranging from 9 to 107 species richness, and their means are between 29.83 and 45.86. The evenness of the two land use systems ranged from 0.23 to 1.62. Lastly, for the two land use systems, the Simpson index (opposite to the Shannon-Wiener diversity index, which gives more weight to dominant species).

Table 4. Diversity and statistical information of forests without and with coffee

Indexes	Forest without coffee				Forest with coffee			
	Min	Max	Mean	St. dev	Min	Max	Mean	St.dev
Diversity index	0.4	3.79	2.69	0.79	0.21	2.82	1.79	0.74
Species richness	19	107	45.86	23.62	9	65	29.83	16.35
Evenness	0.45	1.62	0.85	0.29	0.23	0.96	0.6	0.23
Simpson index	0.16	13.9	2.94	5.38	0.45	4.2	1.25	1.45

The comparison of seedlings, saplings, and mature trees enabled the determination of the forest's regeneration status. Two land use systems have between 22.63 and 16,000 seedlings per hectare. The two land use systems' sapling growth stages varied from 5 to 3287 per hectare. Ultimately, mature trees grow in growth stages ranging from 8 to 740 per hectare (Table 5).

Table 5. The growth form and statistical information of the forest without and with coffee

Growth form	Forest without coffee				Forest with coffee			
	Min	Max	Mean	St. dev	Min	Max	Mean	St. dev
Seedlings	22.63	16000	2886.48	4840.70	27	7110	1694.07	2348.23
Saplings	39	3287	988.03	1163.21	5	1023	319.42	305.55
Mature trees	8	740	393.90	269.93	8	424	267.98	168.06

Two land use schemes primarily influenced bulk density and soil carbon. The range of soil carbon is 50.64–229.83 per hectare. The bulk density of soil similarly falls between 0.75 and 0.97-gram cubic centimeters (Table 6).

Table 6. The forest contribution and statistical information of forest without and with coffee

Contribution of forest	Forest without coffee				Forest with coffee			
	Min	Max	Mean	St. dev	Min	Max	Mean	St. dev
Soil carbon	51.35	229.83	147.18	64.54	50.64	178.09	120.25	50.61
Soil bulk density	0.75	0.92	0.82	0.09	0.81	0.97	0.87	0.09

Graph of the Results of the Meta-Analysis of the Forest without and with Coffee

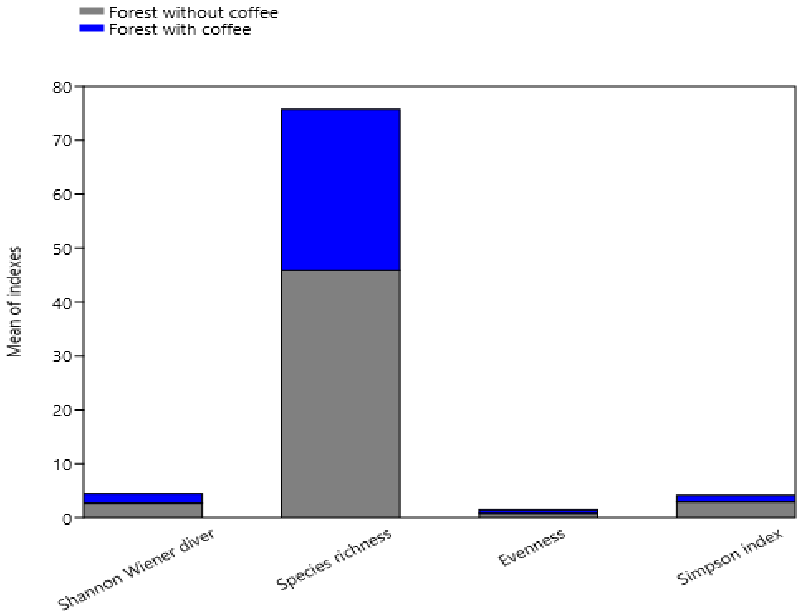

Figure 1. Comparison of the Mean Diversity Information in Two-Land Use Systems

To speed up the differentiation of the diversity information between the coffee- and non-coffee-forests shown in (Figure 1). For forests free of coffee, the listed mean diversity information was preferable.

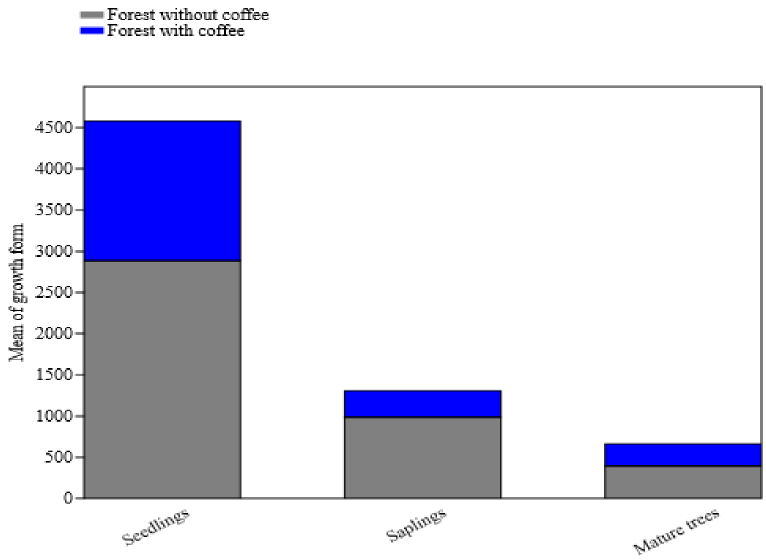

Figure 2. The Growth Form of the Forest without and with Coffee

The average growth form produced superior seedlings, saplings, and mature trees in a forest without coffee. A forest without coffee is better than any of the three growth forms of forests without coffee (Figure 2).

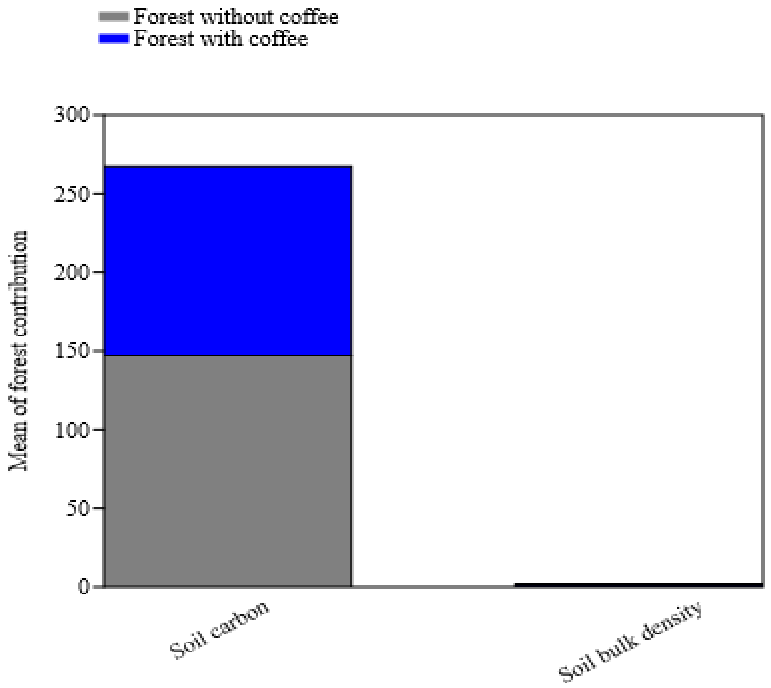

Figure 3. The Mean Soil Carbon and Bulk Density Contribution of the Forest without and with Coffee

Those without coffee had higher mean soil carbon than forests with coffee. The bulk density was lower in two land-use systems. However, forests with coffee had higher soil bulk densities (Figure 3).

This study may have some limitations, such as the sampling techniques used during data collection. The researchers employed systematic random sampling, stratified random sampling, and systematic random sampling in this process. Additionally, plot shapes, including rectangular, square, and nested plots, represent further limitations. The non-uniformity of plot sizes, the distance between transect lines, and soil depths are also limitations of the study. Moreover, the instruments used for data collection have their limitations. Today, there are controversial ideas on woody species composition, soil organic carbon, and bulk density of coffee forests and adjacent natural forests in Ethiopia. Some studies indicate that coffee forests are rich in plant species diversity (Gole et al., 2008; Schmitt, 2006; Senbeta & Denich, 2006). Other researchers oppose these ideas due to intensive coffee forest management, slashing of understory vegetation, and thinning of shade trees affecting the diversity of woody plant species. In this review, species diversity, richness, and regeneration were higher in the natural forest than in the semi-coffee forest in Ethiopia (Tables 1, 2, 4, 5, and Figures 1 and 2).

From a biodiversity standpoint, a significant issue with coffee forest management is its tendency to homogenize natural forests' age, size, and species composition, thereby decreasing their overall diversity. The decline in species diversity, as evidenced by research conducted by Geeraert et al. (2019) and Kewessa et al. (2019), is a cause for concern. Furthermore, there is growing evidence that the expansion of coffee production has adverse effects on the variety and number of forest species and the structure of the forest. This is reflected in the reduced genetic variation, degraded forest structure, decreased capacity to sequester carbon dioxide (Decuyper et al., 2018), a reduced richness and abundance of tree and shrub species (Aerts et al., 2011), and reduced genetic variation have all been reported in previous studies conducted in Ethiopia.

This is because the more structural and floristic diversity of the habitat, the higher the species richness and diversity (Gallina et al., 1996; Donald, 2004); however, further ecosystem disturbance modifies the community structure. The removal of understory trees and shrubs during the conversion of forests into semi-forest coffee systems resulted in the loss of floristic diversity

(Gole, 2003; Donald, 2004). Thus, altering the species diversity of the forest may impact the forest's functional role, and losing species diversity in the semi-forest coffee system will have a detrimental impact on the forest's biodiversity and possibly even on long-term coffee production in the future (Zewdie et al., 2022).

The intensification of forest coffee cultivation negatively impacts the diversity and structure of Ethiopian moist evergreen Afromontane forests to maximize coffee production by reducing ecosystem resilience and disrupting ecosystem services that are linked to coffee yields, like pest control and pollination (Hundera et al., 2013). Management practices like thinning, cutting of undergrowth trees, and frequent pruning of newly growing saplings in the semi-forest coffee results in diversity losses (Nigatu et al., 2017; Gessese, 2018). This activity allows secondary species in disturbed areas to develop swiftly into fully grown trees in the spaces left by managing coffee (Chapman et al., 2002; Bond et al., 2017). On the other hand, climax species in open areas grow more slowly and are less competitive than pioneer species (Schmitt et al., 2010).

Similarly, other authors, Hundera et al. (2013) documented frequent tree-cutting operations, extensive undergrowth slashing, and coffee seedling planting activities impact Ethiopia's montane rainforests. Most coffee growers only keep big trees of different types that can preserve soil moisture and microclimate and have minimal shade intensity. They did not even pay enough attention to allowing the favored tree species to regenerate by keeping their seedlings and saplings. This could significantly impact the preservation of the genetic resources of the variety of woody species found in forest coffee (Nigatu et al., 2017). Cutting giant trees and removing understory vegetation decreased species diversity, simplified the forest structure, and slowed the regeneration of late-successional species, according to a case study from southwest Ethiopia (Arai et al., 2023).

Compared to forests with coffee, forests without coffee have better potential for soil carbon storage. Bulk density was also higher in forests with coffee than without coffee in Anfilo District (Table 3, 6, and Figure 3). This could result from using effective management techniques like burning, weeding, cleaning, and moving biomass. An additional factor could be the age of the coffee plantation (it could be only a few years old and have not seen many disruptions). The other reason could be the buildup of manure and other organic materials in coffee-growing forests, which promotes organic carbon decomposition and growth (Hika et al., 2024). However, other forests without coffee had higher soil organic carbon than those with coffee. Because coffee was managed with lower soil organic matter inputs, large trees were frequently removed from forests having coffee. However, human interventions such as slashing and removing undergrowth vegetation have little effect on forests free of coffee (Betemariyam et al., 2023). According to other researchers, variations in vegetation characteristics, various native forest management practices, soil type and properties, past land use and land cover history, and additional environmental and climatic factors all contribute to variations in soil organic carbon (Dinsa, 2022). In addition, other researchers also point out that the following factors affect soil organic carbon levels in forests without and with coffee: species variability, low soil disturbance, rate of decomposition, soil nutrient availability, climate, and the amount and quality of litter produced (Mengistu & Asfaw, 2019; Hika et al., 2024; Batjes, 2011; Betemariyam et al., 2023).

In most cases, the bulk density of forests with coffee is higher than that of forests without coffee (Table 3, 6, and Figure 3). Because the organic carbon levels of coffee forests are lower, there is less aggregate stability, which contributes to the increased bulk density in these forests (Kassa et al., 2018). The removal of herbs, litter fall, and the comparatively reduced soil organic matter content were the primary factors causing the difference in bulk density between the two land use systems. Soil compaction, soil instability, poor aggregation, organic matter influence on soil structure, saturated water-holding capacity, percolation rates, and soil hydraulic conductivity can all result from plowing. This shows that the soil is compacted, with fewer pore spaces and less water in the soil at field capacity (Kufa, 2013; Adrinal et al., 2021).

CONCLUSION

Forests without coffee had higher woody species diversity, richness, and regeneration than forests with coffee in Ethiopia. We can summarize that forests without coffee provide more ecosystem services (i.e., habitat maintenance, water quality, and erosion control) than coffee forests. Forests without coffee had a higher percentage of soil carbon storage than forests with coffee. The bulk density of coffee-producing forests was higher than that of non-coffee-growing forests. The intensification of forest coffee cultivation to maximize coffee production negatively influences the diversity and structure of Ethiopian natural forests, which breaks the principle of sustainability (equal treatment of the three uses: ecological, social, and economic), but coffee producers focus only on economic benefits. When comparing the diversity of woody species and soil organic carbon in Ethiopian natural forests and coffee-based forests, the other researchers should concentrate on the level of forest disturbance under study. Because of the significant strain on species diversity and soil carbon. In addition, when examining species diversity and soil carbon, we should consider the accessibility and distance of specific natural forests from settlement areas. Finally, when studying forest-related studies, we must also take account of the wildlife population that is present in the natural forest. Documentation of woody tree or shrub species will be required for forests without and with coffee for immediate conservation, either ex-situ or in situ. Pruning will be required to minimize crown coverage to increase the density of the tree in forest coffee. For the long-term effects of coffee on species diversity, regeneration, and soil physico-chemical properties, a permanent plot-level study will be preferable.

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