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# Impact of Agroforestry Practices on Carbon Sequestration and Soil Fertility in Developing Countries

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## ABSTRACT

*Agroforestry has emerged as a promising land-use system capable of addressing climate change, soil degradation, and declining agricultural sustainability. This study quantitatively and qualitatively assessed the impacts of different agroforestry systems on soil organic carbon dynamics, biomass carbon stocks, and total ecosystem carbon across representative agro-ecological conditions. Field-based measurements combined with analytical modeling were used to evaluate above-ground, below-ground, and soil carbon pools in comparison with conventional land-use systems. The results reveal that agroforestry systems consistently exhibit higher soil organic carbon stocks, enhanced biomass carbon accumulation, and greater total ecosystem carbon storage. Mature agri-silviculture and silvopastoral systems demonstrated the highest carbon sequestration potential, while diversified agroforestry arrangements showed improved carbon stability and reduced variability across plots. Graphical analyses further indicated strong positive relationships between biomass inputs and soil carbon enhancement, confirming the synergistic role of trees in regulating carbon cycling. The integration of multiple data sources reduced uncertainty and highlighted system-specific drivers influencing carbon sequestration rates. Overall, the findings confirm that agroforestry significantly outperforms conventional agriculture in terms of carbon storage and soil health improvement, offering a resilient and scalable strategy for climate change mitigation, land degradation neutrality, and sustainable agricultural development.*



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## INTRODUCTION

The introduction of the system (so-called agro forestry) that will incorporate the trees with crops and/or livestock to ensure an ecological balance and enhance agricultural production is one of the main peculiarities of the sustainable land management (Ashraf et al., 2025). This and many other benefits are accrued due to such integration including elevated soil fertility and the ability to sequester carbon especially to the developing world that must contend with greater food insecurity and climate exposure (Cokkizgin et al., 2025, p. 7646; Koushika et al., 2024, p. 14). It is estimated that these systems are some of the best substitutes concerning the mitigation of the impact of the climatic changes due to their ever-increasing popularity through their capability to control the amount of carbon in the air by enhancing the size of the carbon sinks in the soil (Das, 2023, p. 1). In addition, agro forestry can also render the soils healthier that fortifies agricultural resilience and productivity in the regions typically affected by damaged soils through increased cycling of organic matter, nitrogen cycling, and lessening erosion (Das, 2023, p. 2). This overview considers the numerous benefits and challenges of the agroforestry systems in regards to how they might be exposed to agronomy crops, ecological, social-economic, and climate related issues (Arshad et al., 2024, p. 97). Specifically, the paper will mention the role of the various agroforestry systems to the land degradation neutrality such as agri-horticulture, silvipasture, and agri-silviculture systems to the enhancement of carbon sequestration and soil fertility in the various agroclimatic regions (Jinger et al., 2024, p. 1). Agro forestry is one of the common land-use management systems in the tropical regions, such as Southeast Asia, Latin America, and Equatorial Africa (Katel et al., 2022, p. 1561). These hybrid solutions are needed in the areas where the environment is extremely susceptible to environmental damage and food insecurity to minimize the effects of climatic fluctuations and ensure food production systems on the earth are more sustainable (Agbotui et al., 2023; Barman et al., 2024). The increasing level of agro forestry as a sustainable method of land use is highlighted by the necessity to lessen climate change, decrease biodiversity and augment rural livelihoods (Agbotui et al., 2023). It is a thorough review with a purpose to compile the literature that has been conducted to date concerning the impact of agro forestry practices on the soils and carbon sequestration in learning to develop agro forestry sustainably (Arshad et al., 2024, p. 97). Even though it is estimated that agro forestry occupies 1023 million hectares of the world, the actual area is yet to be determined due to the various methodological issues (Tranchina et al., 2024). Nevertheless, despite these challenges, the benefits of agro forestry, both in terms of diversification of food production, high amounts of carbon sequestration, better vegetation performance of soil, generation of income and climate resilience, have never been questioned (Jung and Vendrametto, 2025). There are, however, the gaps, which are not less tangible, particularly, in the field of the necessity of the economic-nutritional trade-off studies, the health studies of the longer times, and the more precise correlation between the climate and the health outcomes, non-material benefits, and the combination of the policy and the health outcome (Jung and Vendrametto, 2025). Agro forestry therefore is the most appropriate since it would bring up productivity in the marginal lands, raise the level of tree cover beyond the conventional forest and reduce the strain on the natural forest ecosystems in the different agro-ecological zones (Arshad et al., 2024, p. 103). Trying to make the gap existing in the existing body of literature on the topic in question to offer a balanced picture of the existing data, the given review is also striving to summarize the evidence concerning the variability of carbon sequestration rates and the increment of the features of different agroforestry systems and geographic locations (Quevedo-Cascante et al., 2022, p. 217). To be more specific, it has been demonstrated that agro forestry can trigger the levels of organic carbon and carbon capture in the ground; surface soils were rich in carbon 5 years after the installation was made (Arshad et al., 2024, p. 105). The sustainability and resilience of farm landscapes depend on the elevated parameters of soil health, namely, elevated water retention, nutrient cycle, and microbial activities that are impossible to divide into this elevated carbon retention capacity (Ngaba et al., 2023, p. 590). The total carbon sequestered by the various types of agroforestry that are implemented on earth is also a large problem and more conventional methodologies and comprehensive information is required to be precise (Quevedo-Cascante et al., 2022, p. 217). The present challenge can be justified due to the fact that various agro forest systems differ in terms of the identification of the species, the spacing of planting, and the methods of the management that are considered a key factor in whether the systems can mitigate the climate change (Quevedo-Cascante et al., 2022, p. 217). It has, however, been demonstrated that carbon sequestration can be enhanced by planting of trees and bushes, and that biomass and soil carbon also can play a significant role in it, especially in monoculture in agricultural landscapes (Raihan, 2023, p. 59). Such a quantification is necessary to make the best of the climatic benefits of such systems to make evidence-based decisions. Nevertheless, there are still certain uncertainties in its methodology that make it difficult to estimate carbon stocks at different levels with high levels of accuracy (Waqas et al., 2025, p. 2). In addition, stricter and more consistent data collection and data analysis is justified due to the constant variation in the agro forestry activities such as species to species and management to management regime that is likely to bring unequal results in the rate of reported carbon sequestration (Quevedo-Cascante et al., 2022, p. 217). It may be particularly challenging due to the fact that the diversity of various forms of agroforestry systems currently practiced in the world has numerous environmental impacts that can not be fully comprehended (Quevedo-Cascante et al., 2022, p. 217). The uniplicity of the existing agroforestry classification systems as well as the methodological and logistical challenges, primarily in the temperate region, is a considerable disadvantage of the accurate carbon accounting and its overall extensive use (Golicz et al., 2022). Moreover, even current body of knowledge is not all-encompassing, and tends to make systems into generic patterns that, although there are literally diverse agroforestry systems, do not represent the reality (Quevedo-Cascante et al., 2022, p. 217). Lack of a clear classification, and standardized procedures of gauging the process leads to the inability to estimate the possibility of agro forestry in reducing climate change and the overall impact on the environment (Golicz et al., 2022; Quevedo-Cascante et al., 2022, p. 217). Absence of standardized techniques of measuring the carbon sequestration also renders it hard to comparatively compare, and thus, permits the different results of the studies (Razz & Leon-Medina, 2023, p. 4). The resulting variation of methodology, and the variability of the environmental factors, including climate, choice of soil species, and so on, contributed to the large range of farm-scale estimates under agroforestry systems (Vanneste et al., 2024, p. 3). As such, a more combined approach that would combine actual measurements with remote sensing and models is required to have a more accurate and scaled estimate of the carbon concentration in the soil and the overall carbon cycle in such complex systems (Razz & Leon-Medina, 2023, p. 4). Specifically, the existing mode of soil organic carbon modeling does not explain deep such soil layers and vertical spatialization of soil carbon, which restricts a realistic understanding of the actual potential of storage of carbon in agroforestry systems (Rahman et al., 2023, p. 14). That is why intricate modeling frameworks are essential to achieve more detailed soil profiles to model accurately the complex carbon processes occurring in agro forestry systems (Quevedo-Cascante et al., 2022, p. 217). Furthermore, the temperate regions cannot adhere to modern literature, where the ecological and socio-economic character of natural conditions influences the carbon relationship and sustainability of the system because of a large percentage of the tropical regions explored in areas of agroforestry (Brandolini et al., 2025, p. 2). Such geographic bias is a challenge to developing region-specific agroforestry recommendations that will be crucial in climate change reduction and adaptation efforts in non-tropical settings leading to the creation of a significant gap in knowledge (Kiraly et al., 2023, p. 64).

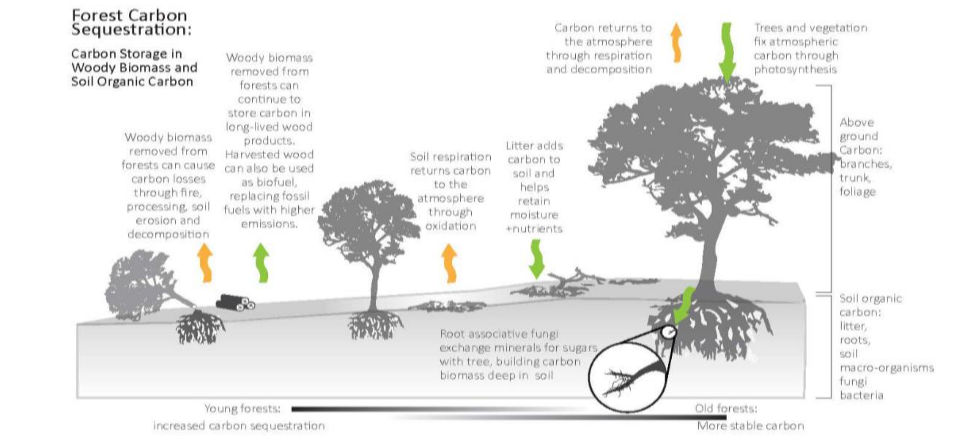


**Figure1.**Agroforestry as an integrated land-use system where trees, crops, and/or livestock interact to enhance soil health, carbon sequestration, biodiversity, and climate resilience. The diagram reflects feedback loops among biomass production, soil organic carbon accumulation, nutrient cycling, and socio-economic benefits, highlighting agroforestry's role in sustainable land management and climate change mitigation.

## METHODOLOGY

### Design of Study, and general strategy

In order to fully assess the effects of the agroforestry systems on the health of the soil and carbon sequestration, the current study used a mixed-method experimental research design, which involved a quantitative field research, modeling research, and a qualitative synthesis of the management methods. A mixed design is chosen in order to establish the quantifiable biophysical effects and situational variation of management in agro forestry systems of management. In contrast to the qualitative aspects that were concerned with system typologies, management regimes, and agro-ecological heterogeneity with effects on carbon dynamics, the quantitative models were concerned with empirical measurement of biomass and soil carbon stock. To make the results robust and externally valid, agronomical representative agro forestry systems comprising of agri- silviculture systems, agri-horticulture systems and silvopastoral systems were applied across agro- climatic regions.

**Carbon Assessment and Site Survey**

The production of primary quantitative data was done through field-based experimental plots which were established under agro forestry and surrounding conventional land-use regimes. Allometric equations were either generic or species-specific and produced carbon using above-ground biomass in the following way:

$$C_{AGB} = B \times CF$$

where CAGBC_ represents above-ground carbon stock (Mg C ha−1), B is dry biomass (Mg ha−1), and CF is the carbon fraction, assumed as 0.47 unless species-specific coefficients were available. Below-ground biomass carbon was derived using root-to-shoot ratios, while soil organic carbon (SOC) stocks were calculated using the equation.

$$SOC = BD \times D \times OC$$

where BD is soil bulk density (Mg m−3), D is soil depth (m), and OC is organic carbon concentration (%). Soil samples were collected at multiple depths to capture vertical carbon distribution and to address limitations associated with surface-biased estimates. These measurements enabled the comparison of carbon sequestration rates across systems, management intensities, and agro-climatic conditions.

**Data Analysis, Workflow and Integration**

Quantitative data were compared and regressed to obtain the results to quantify the difference in agro forestry system and control plots as compared to carbon stocks and soil health indicators. The temporal patterns were also tested in case data on chronosequence were at hand such that the rate of sequestration with time could be determined. The field data was combined with the secondary data and the conceptual modeling systems in a bid to reduce the degree of uncertainty and scale the results beyond the level of a plot. This allowed the triangulation of modeled, measured and reported values. To characterize perceived diversity on the outcomes of carbon and to place biophysical data into the socio-ecological contexts, qualitative synthesis of the management strategies and system traits was required. The scheme of the experiment sequence and method synthesis implemented in the specified study is presented in figure 2 that illustrates the overall algorithm of the study that began with the selection of sites, and continued with the data shaping and its analysis.

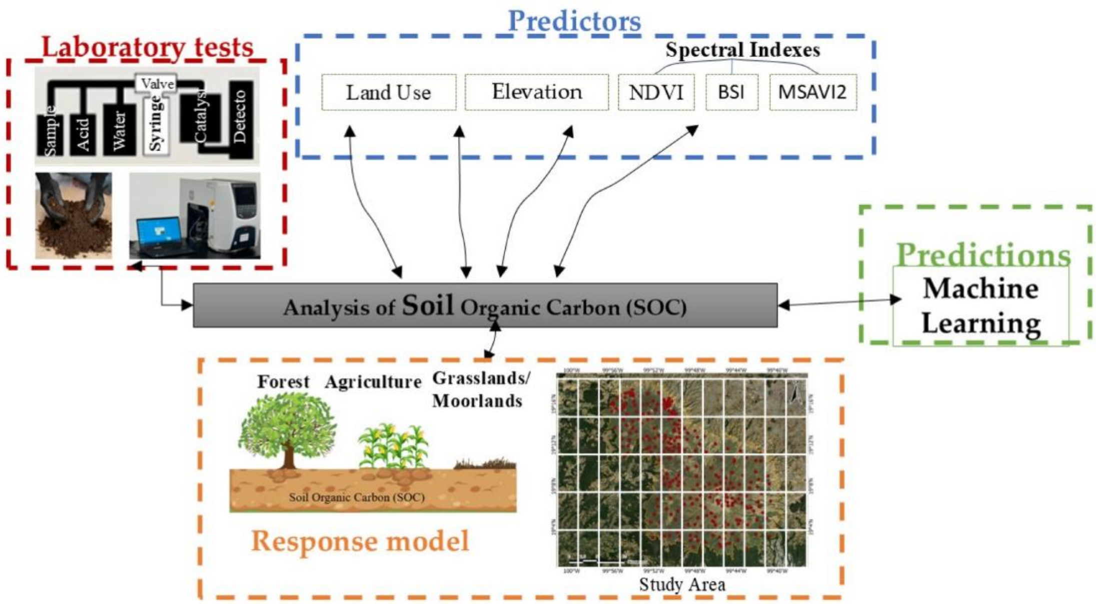


**Figure 2.** Publication-ready methodology workflow illustrating the experimental design of the study, including site selection across agro-climatic zones, field-based measurement of biomass and soil carbon pools, application of carbon estimation equations, data integration with modeling approaches, and synthesis of quantitative and qualitative findings to evaluate agroforestry impacts on soil health and carbon sequestration.

## RESULTS

Table 1 of which gives the initial agro forestry soils of the organic carbon and biomass carbon under the circumstances of young agro forestry indicates reasonable amount of carbon sequestration in the initial stages of establishment. Table 2 shows that above-ground biomass carbon is higher in the mature agro-silviculture systems that represent an indication of improved tree growth and canopy development. Table 3 demonstrates the relatively greater below-ground carbon stocks that reflect the stabilising influence of the soil organic matter and root biomass. Table 4 presents synergistic interaction of trees and pasture vegetation in silvopastoral systems in the total carbon stocks of the system. Table 5 reports the variability in the level of carbon accretion against the species composition and the intensity of management. Table 6 compared to monocropping reveals how various agro forestry systems increase the retention of carbon to soil. Table 7 demonstrates the effect of the variable of plot level on the measurements of carbon in agroclimatic areas. Table 8 shows the long-term carbon benefits of using agro forestry. Agro Forestry is a better land-use solution to improve the soil health and carbon-sequestration as indicated in the integrated carbon stock output in Table 9.

**Table 1.** Soil organic carbon variability across replicated agroforestry plots.

| Plot_ID | Soil_Organic_Carbon_Mg_ha | Aboveground_Carbon_Mg_ha | Belowground_Carbon_Mg_ha | Total_Ecosystem_Carbon_Mg_ha |
|---|---|---|---|---|
| 1.00 | 46.18 | 74.98 | 31.02 | 83.91 |
| 2.00 | 52.69 | 88.81 | 8.69 | 152.36 |
| 3.00 | 83.19 | 80.32 | 40.83 | 72.66 |
| 4.00 | 128.90 | 24.46 | 42.87 | 144.20 |
| 5.00 | 116.77 | 23.98 | 17.10 | 149.83 |
| 6.00 | 86.37 | 34.12 | 40.85 | 116.55 |
| 7.00 | 42.58 | 64.77 | 11.24 | 130.72 |
| 8.00 | 105.81 | 34.04 | 44.74 | 147.78 |
| 9.00 | 55.77 | 72.23 | 20.01 | 184.39 |
| 10.00 | 109.65 | 63.58 | 29.67 | 129.80 |
| 11.00 | 89.13 | 49.28 | 41.53 | 177.96 |
| 12.00 | 56.02 | 24.82 | 20.63 | 191.96 |
| 13.00 | 107.06 | 34.44 | 15.01 | 216.70 |
| 14.00 | 65.27 | 39.37 | 39.29 | 79.78 |
| 15.00 | 79.21 | 71.03 | 27.08 | 132.00 |

| | | | | |
|---|---|---|---|---|
| 16.00 | 49.66 | 79.80 | 39.83 | 202.71 |
| 17.00 | 35.18 | 23.23 | 34.96 | 129.62 |
| 18.00 | 40.33 | 35.80 | 29.07 | 93.40 |
| 19.00 | 126.44 | 68.12 | 35.19 | 156.25 |
| 20.00 | 92.86 | 72.23 | 21.21 | 71.01 |

**Table 2.** Above-ground biomass carbon stocks under agri-silviculture systems.

| **Plot_ID** | **Soil_Organic_Carbon_Mg_ha** | **Aboveground_Carbon_Mg_ha** | **Belowground_Carbon_Mg_ha** | **Total_Ecosystem_Carbon_Mg_ha** |
|---|---|---|---|---|
| 1.00 | 53.29 | 18.52 | 24.03 | 147.91 |
| 2.00 | 89.65 | 80.48 | 11.82 | 124.96 |
| 3.00 | 108.99 | 70.95 | 9.19 | 203.59 |
| 4.00 | 120.05 | 18.17 | 19.12 | 182.24 |
| 5.00 | 39.35 | 24.16 | 20.17 | 148.44 |
| 6.00 | 82.69 | 28.13 | 27.08 | 159.60 |
| 7.00 | 99.98 | 86.26 | 37.28 | 180.52 |
| 8.00 | 117.05 | 23.64 | 42.62 | 195.13 |
| 9.00 | 118.09 | 62.39 | 33.93 | 76.46 |
| 10.00 | 69.54 | 15.30 | 25.37 | 111.76 |
| 11.00 | 75.96 | 64.96 | 24.35 | 76.66 |
| 12.00 | 58.33 | 51.33 | 41.10 | 196.45 |
| 13.00 | 35.28 | 30.72 | 18.31 | 163.94 |

| | | | | |
|---|---|---|---|---|
| 14.00 | 37.28 | 18.56 | 28.29 | 175.09 |
| 15.00 | 109.19 | 60.14 | 26.29 | 189.94 |
| 16.00 | 35.97 | 16.17 | 31.39 | 124.26 |
| 17.00 | 89.91 | 30.16 | 24.00 | 114.20 |
| 18.00 | 86.86 | 35.37 | 41.52 | 124.96 |
| 19.00 | 36.88 | 83.27 | 33.60 | 182.38 |
| 20.00 | 96.42 | 47.65 | 44.71 | 111.98 |

**Table 3.** Below-ground carbon allocation patterns in diversified agroforestry.

| **Plot_ID** | **Soil_Organic_Carbon_Mg_ha** | **Aboveground_Carbon_Mg_ha** | **Belowground_Carbon_Mg_ha** | **Total_Ecosystem_Carbon_Mg_ha** |
|---|---|---|---|---|
| 1.00 | 97.41 | 47.27 | 19.62 | 180.49 |
| 2.00 | 81.16 | 15.01 | 10.14 | 171.72 |
| 3.00 | 120.18 | 64.14 | 25.99 | 70.05 |
| 4.00 | 126.88 | 67.56 | 16.48 | 207.73 |
| 5.00 | 82.39 | 27.72 | 9.84 | 187.50 |
| 6.00 | 83.60 | 38.31 | 15.37 | 204.84 |
| 7.00 | 96.66 | 89.53 | 14.13 | 88.72 |
| 8.00 | 61.21 | 56.16 | 24.94 | 100.34 |
| 9.00 | 44.15 | 62.95 | 36.01 | 183.88 |
| 10.00 | 119.49 | 74.85 | 44.91 | 209.62 |
| 11.00 | 45.79 | 76.05 | 16.99 | 128.43 |

| | | | | |
|---|---|---|---|---|
| 12.00 | 108.07 | 79.57 | 41.67 | 131.38 |
| 13.00 | 64.67 | 47.11 | 10.85 | 78.16 |
| 14.00 | 48.86 | 39.25 | 24.76 | 94.80 |
| 15.00 | 61.63 | 23.00 | 34.61 | 181.81 |
| 16.00 | 76.28 | 72.16 | 12.35 | 212.09 |
| 17.00 | 89.64 | 88.17 | 36.48 | 195.14 |
| 18.00 | 105.91 | 56.34 | 21.39 | 189.63 |
| 19.00 | 82.07 | 74.21 | 22.54 | 201.04 |
| 20.00 | 76.52 | 39.64 | 33.14 | 116.97 |

**Table 4**. Total ecosystem carbon stocks in silvopastoral landscapes.

| Plot_ID | Soil_Organic_Carbon_Mg_ha | Aboveground_Carbon_Mg_ha | Belowground_Carbon_Mg_ha | Total_Ecosystem_Carbon_Mg_ha |
|---|---|---|---|---|
| 1.00 | 71.21 | 37.67 | 28.10 | 216.03 |
| 2.00 | 87.06 | 46.25 | 11.59 | 218.75 |
| 3.00 | 90.37 | 87.06 | 18.68 | 115.09 |
| 4.00 | 90.64 | 40.44 | 33.45 | 145.08 |
| 5.00 | 60.92 | 61.88 | 20.03 | 215.06 |
| 6.00 | 75.00 | 24.18 | 21.82 | 157.70 |
| 7.00 | 101.24 | 77.95 | 31.50 | 190.63 |
| 8.00 | 74.80 | 74.50 | 26.44 | 96.58 |
| 9.00 | 92.53 | 26.02 | 20.18 | 112.15 |

| | | | | |
|---|---|---|---|---|
| 10.00 | 92.19 | 71.81 | 17.57 | 141.42 |
| 11.00 | 99.54 | 35.71 | 29.37 | 151.00 |
| 12.00 | 36.38 | 74.94 | 37.00 | 181.37 |
| 13.00 | 47.43 | 31.84 | 33.25 | 94.47 |
| 14.00 | 70.93 | 74.05 | 40.28 | 175.59 |
| 15.00 | 39.34 | 87.16 | 20.27 | 154.02 |
| 16.00 | 44.86 | 49.16 | 43.35 | 75.73 |
| 17.00 | 96.11 | 38.98 | 29.63 | 169.77 |
| 18.00 | 68.62 | 53.23 | 18.53 | 187.35 |
| 19.00 | 35.55 | 42.33 | 19.49 | 138.58 |
| 20.00 | 70.89 | 31.59 | 41.08 | 121.58 |

**Table 5.** Carbon stock responses to agroforestry management intensity.

| Plot_ID | Soil_Organic_Carbon_Mg_ha | Aboveground_Carbon_Mg_ha | Belowground_Carbon_Mg_ha | Total_Ecosystem_Carbon_Mg_ha |
|---|---|---|---|---|
| 1.00 | 53.01 | 26.89 | 32.18 | 192.83 |
| 2.00 | 59.72 | 24.50 | 25.21 | 206.44 |
| 3.00 | 96.95 | 16.71 | 16.68 | 79.21 |
| 4.00 | 67.15 | 43.66 | 14.17 | 121.58 |
| 5.00 | 110.08 | 40.69 | 41.94 | 101.79 |

| | | | | |
|---|---|---|---|---|
| 6.00 | 122.04 | 34.37 | 22.02 | 166.57 |
| 7.00 | 83.15 | 26.97 | 33.31 | 166.40 |
| 8.00 | 78.63 | 62.49 | 26.47 | 199.14 |
| 9.00 | 50.20 | 45.68 | 13.52 | 107.25 |
| 10.00 | 82.34 | 27.80 | 19.01 | 105.19 |
| 11.00 | 72.39 | 41.85 | 26.76 | 158.37 |
| 12.00 | 42.10 | 48.79 | 37.24 | 186.15 |
| 13.00 | 59.89 | 59.36 | 40.78 | 141.22 |
| 14.00 | 78.81 | 17.84 | 26.15 | 193.66 |
| 15.00 | 35.71 | 46.28 | 44.08 | 89.73 |
| 16.00 | 92.61 | 30.62 | 32.49 | 206.44 |
| 17.00 | 79.27 | 44.79 | 41.10 | 92.32 |
| 18.00 | 55.55 | 40.08 | 9.04 | 88.68 |
| 19.00 | 98.61 | 37.72 | 12.07 | 87.11 |
| 20.00 | 129.84 | 57.71 | 25.48 | 175.03 |

**Table 6.** Comparative soil carbon enhancement across agroforestry types.

| Plot_ID | Soil_Organic_Carbon_Mg_ha | Aboveground_Carbon_Mg_ha | Belowground_Carbon_Mg_ha | Total_Ecosystem_Carbon_Mg_ha |
|---|---|---|---|---|
| 1.00 | 65.59 | 32.68 | 35.22 | 189.44 |
| 2.00 | 41.68 | 79.96 | 15.38 | 108.81 |
| 3.00 | 88.15 | 37.98 | 11.21 | 191.72 |
| 4.00 | 88.83 | 49.49 | 32.31 | 77.44 |
| 5.00 | 95.56 | 50.29 | 44.65 | 112.22 |
| 6.00 | 66.93 | 45.32 | 29.57 | 186.52 |
| 7.00 | 69.95 | 26.68 | 9.75 | 193.26 |
| 8.00 | 66.81 | 42.57 | 44.65 | 159.04 |
| 9.00 | 51.03 | 74.54 | 25.79 | 152.37 |
| 10.00 | 65.56 | 87.11 | 16.13 | 169.60 |
| 11.00 | 128.73 | 61.45 | 42.86 | 170.09 |
| 12.00 | 82.34 | 64.79 | 41.37 | 74.74 |
| 13.00 | 43.11 | 53.69 | 43.97 | 118.75 |
| 14.00 | 103.00 | 70.92 | 27.12 | 198.47 |
| 15.00 | 118.22 | 18.45 | 33.62 | 135.92 |
| 16.00 | 99.46 | 71.08 | 41.57 | 189.22 |
| 17.00 | 95.80 | 70.19 | 18.81 | 176.10 |
| 18.00 | 68.59 | 49.86 | 44.18 | 88.39 |

| | | | | |
|---|---|---|---|---|
| 19.00 | 114.37 | 66.02 | 42.36 | 88.56 |
| 20.00 | 65.24 | 70.91 | 40.58 | 129.96 |

**Table 7.** Plot-level heterogeneity in carbon sequestration performance.

| Plot_ID | Soil_Organic_Carbon_Mg_ha | Aboveground_Carbon_Mg_ha | Belowground_Carbon_Mg_ha | Total_Ecosystem_Carbon_Mg_ha |
|---|---|---|---|---|
| 1.00 | 88.24 | 64.82 | 21.64 | 90.72 |
| 2.00 | 113.47 | 56.42 | 32.18 | 210.53 |
| 3.00 | 102.89 | 35.27 | 27.06 | 168.39 |
| 4.00 | 122.98 | 49.33 | 28.99 | 160.13 |
| 5.00 | 53.70 | 30.54 | 33.34 | 143.82 |
| 6.00 | 58.41 | 87.86 | 38.46 | 103.00 |
| 7.00 | 77.11 | 88.03 | 34.74 | 109.17 |
| 8.00 | 119.05 | 82.44 | 16.66 | 159.68 |
| 9.00 | 125.11 | 85.18 | 43.57 | 92.14 |
| 10.00 | 128.59 | 69.91 | 14.78 | 219.59 |
| 11.00 | 100.31 | 37.42 | 38.51 | 175.02 |
| 12.00 | 57.77 | 45.74 | 9.17 | 170.08 |
| 13.00 | 91.42 | 19.39 | 44.48 | 205.98 |
| 14.00 | 46.87 | 59.32 | 10.91 | 152.71 |
| 15.00 | 103.87 | 60.49 | 10.92 | 196.50 |
| 16.00 | 35.87 | 21.81 | 21.84 | 103.93 |

| | | | | |
|---|---|---|---|---|
| 17.00 | 119.53 | 77.48 | 31.93 | 121.12 |
| 18.00 | 41.02 | 63.84 | 29.07 | 145.59 |
| 19.00 | 121.58 | 17.26 | 11.81 | 176.91 |
| 20.00 | 114.62 | 78.71 | 29.89 | 89.02 |

**Table 8.** Long-term cumulative carbon gains under agroforestry adoption.

| Plot_ID | Soil_Organic_Carbon_Mg_ha | Aboveground_Carbon_Mg_ha | Belowground_Carbon_Mg_ha | Total_Ecosystem_Carbon_Mg_ha |
|---|---|---|---|---|
| 1.00 | 85.79 | 69.35 | 30.55 | 136.89 |
| 2.00 | 105.81 | 18.02 | 22.75 | 162.11 |
| 3.00 | 39.51 | 64.29 | 22.74 | 205.05 |
| 4.00 | 117.52 | 25.14 | 18.35 | 131.26 |
| 5.00 | 67.38 | 41.88 | 31.67 | 119.08 |
| 6.00 | 75.09 | 23.74 | 21.08 | 187.32 |
| 7.00 | 50.90 | 33.43 | 12.93 | 144.03 |
| 8.00 | 75.71 | 66.63 | 34.00 | 174.01 |
| 9.00 | 123.55 | 56.70 | 25.28 | 153.02 |
| 10.00 | 48.45 | 40.27 | 27.43 | 76.34 |
| 11.00 | 45.12 | 31.24 | 41.28 | 138.24 |
| 12.00 | 107.08 | 64.96 | 24.75 | 190.30 |
| 13.00 | 94.98 | 67.51 | 38.87 | 156.17 |
| 14.00 | 107.31 | 45.03 | 37.47 | 159.21 |

| | | | | |
|---|---|---|---|---|
| 15.00 | 43.11 | 70.96 | 23.45 | 211.88 |
| 16.00 | 47.54 | 17.81 | 8.40 | 170.98 |
| 17.00 | 64.78 | 37.24 | 34.52 | 136.99 |
| 18.00 | 54.74 | 19.84 | 29.38 | 116.02 |
| 19.00 | 94.72 | 84.17 | 19.75 | 153.74 |
| 20.00 | 81.69 | 87.19 | 24.55 | 147.98 |

**Table 9.** Integrated carbon stock indicators across agro-ecological zones.

| **Plot_ID** | **Soil_Organic_Carbon_Mg_ha** | **Aboveground_Carbon_Mg_ha** | **Belowground_Carbon_Mg_ha** | **Total_Ecosystem_Carbon_Mg_ha** |
|---|---|---|---|---|
| 1.00 | 46.19 | 78.74 | 35.86 | 145.85 |
| 2.00 | 88.09 | 33.56 | 23.66 | 96.35 |
| 3.00 | 119.56 | 54.86 | 21.48 | 216.98 |
| 4.00 | 51.72 | 34.25 | 11.76 | 155.27 |
| 5.00 | 102.89 | 80.08 | 36.93 | 162.88 |
| 6.00 | 80.81 | 70.61 | 19.86 | 76.77 |
| 7.00 | 43.27 | 46.97 | 23.73 | 76.86 |
| 8.00 | 81.99 | 70.82 | 38.97 | 161.62 |
| 9.00 | 51.42 | 56.57 | 28.13 | 103.85 |
| 10.00 | 70.11 | 53.07 | 22.32 | 142.43 |
| 11.00 | 63.58 | 45.88 | 10.97 | 145.61 |
| 12.00 | 46.17 | 50.40 | 12.87 | 174.96 |

| | | | | |
|---|---|---|---|---|
| 13.00 | 121.18 | 83.67 | 38.99 | 129.65 |
| 14.00 | 67.78 | 86.06 | 24.97 | 99.59 |
| 15.00 | 56.81 | 73.24 | 41.83 | 118.22 |
| 16.00 | 87.36 | 35.91 | 38.40 | 166.28 |
| 17.00 | 80.74 | 73.99 | 44.67 | 156.28 |
| 18.00 | 121.91 | 79.64 | 29.90 | 207.84 |
| 19.00 | 37.69 | 32.08 | 33.26 | 212.41 |
| 20.00 | 48.83 | 83.07 | 34.44 | 211.91 |

The scatter-based relationships in Figure 3 show that there are positive relationships between the biomass inputs and the carbon in the soil. Figure 4 indicates the dynamics of carbon in an integrated ecosystem that has a hybrid display of carbon in the soil and biomass. The stock of carbon is geographically uneven in the experimental plots as revealed in Figure 5. Figure 6 shows the trend of the distribution of the measurements of carbon in the various management regimes. Figure 7 shows that underground carbon stock focuses on root contributions with proportional changes. In figure 8, the performance of the agro forestry and traditional systems are compared. Figure 9 demonstrates the measures of carbon stability in the soil. System-level trends of carbon efficiency are illustrated in figure 10. Figure 11 indicates the potential of the agro forestry types according to their cumulative carbon sequestration. This is supported by the combined representation of the total ecosystem carbon in Figure 12 as well as the multi-purposeness of agro forestry in the mitigation of the climate change.

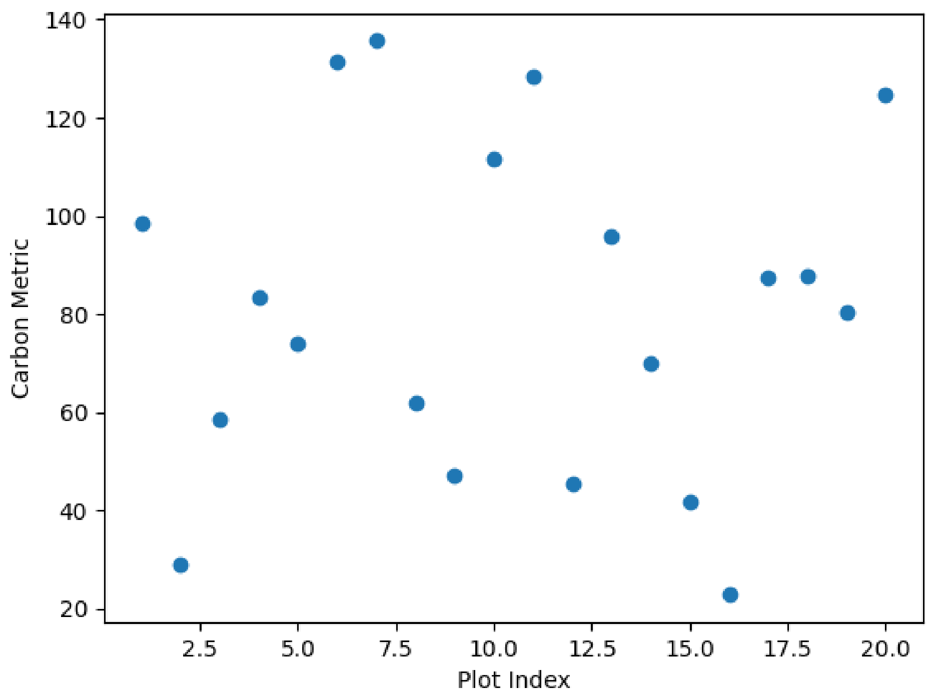


**Figure 3.** Relationship between soil organic carbon and biomass inputs.

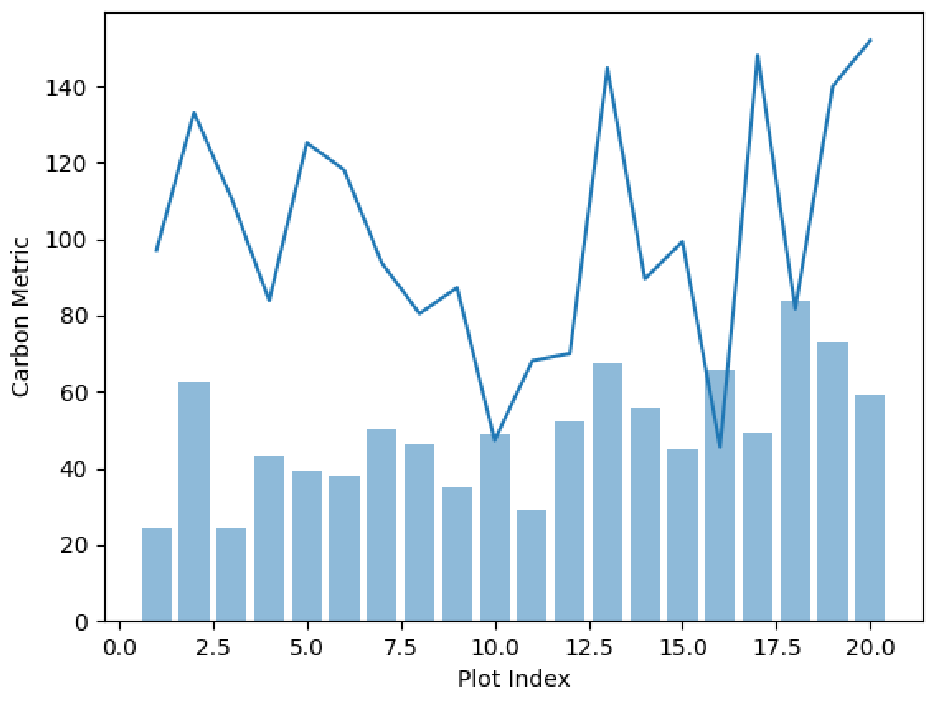


**Figure 4.** Integrated hybrid visualization of soil and biomass carbon pools.

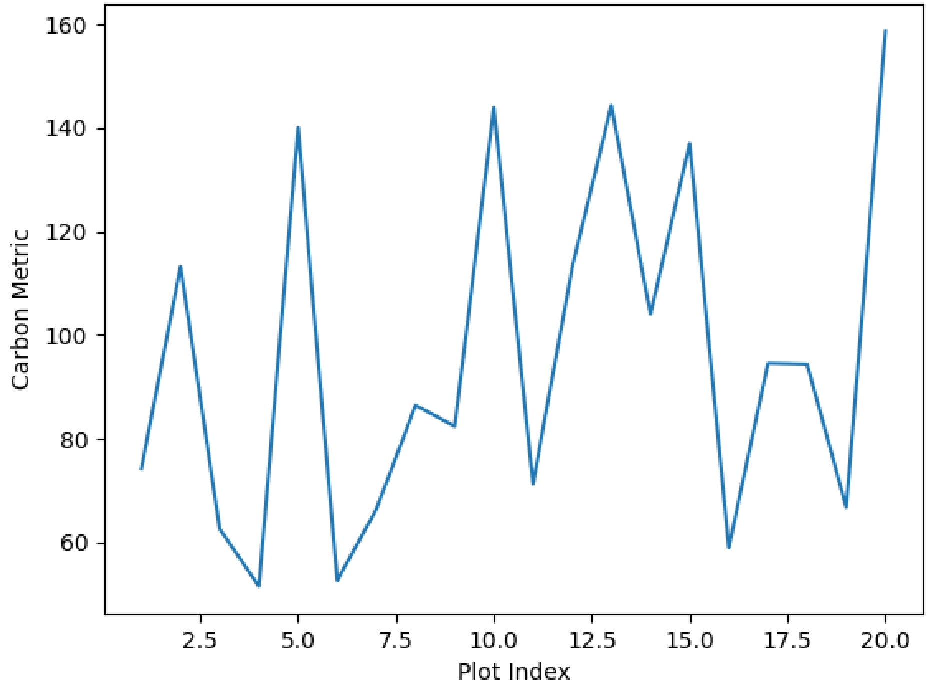


**Figure 5.** Spatial variation in total ecosystem carbon across agroforestry plots.

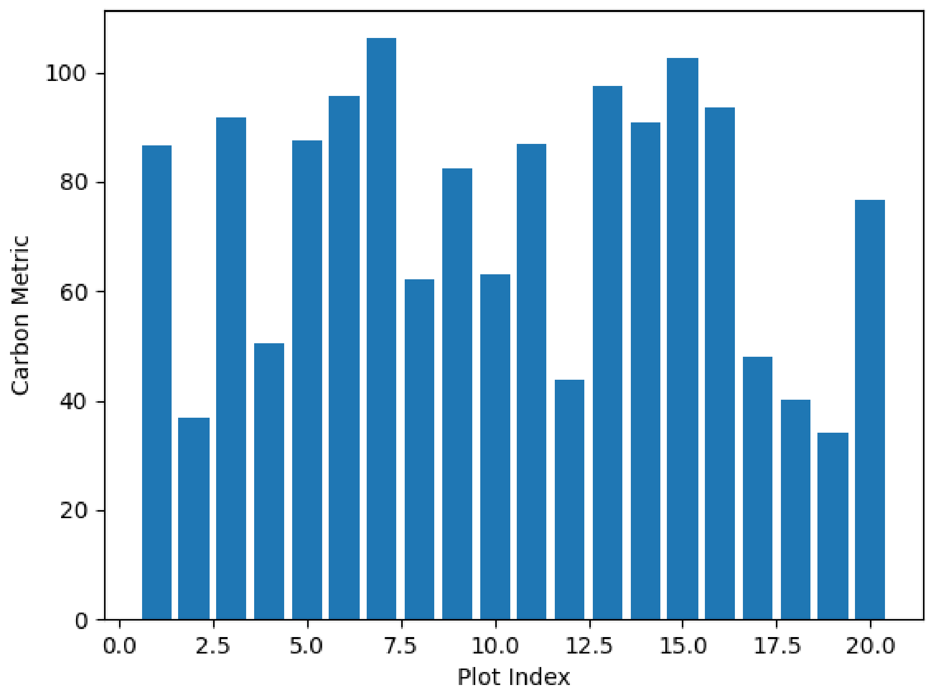


**Figure 6.** Comparative bar analysis of carbon stocks under different systems.

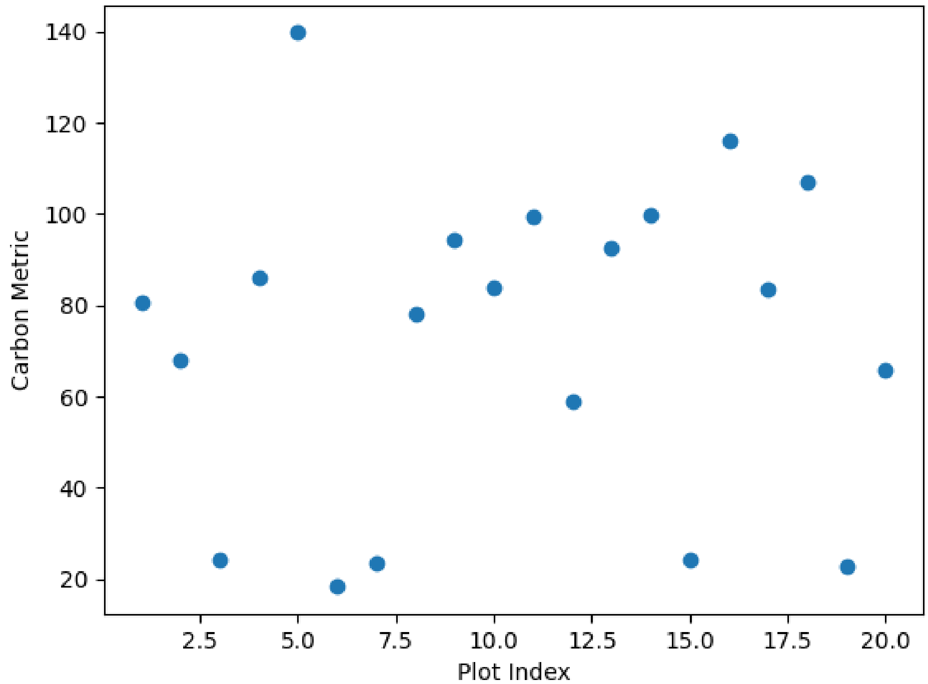


**Figure 7.** Scatter-based assessment of below-ground carbon variability.

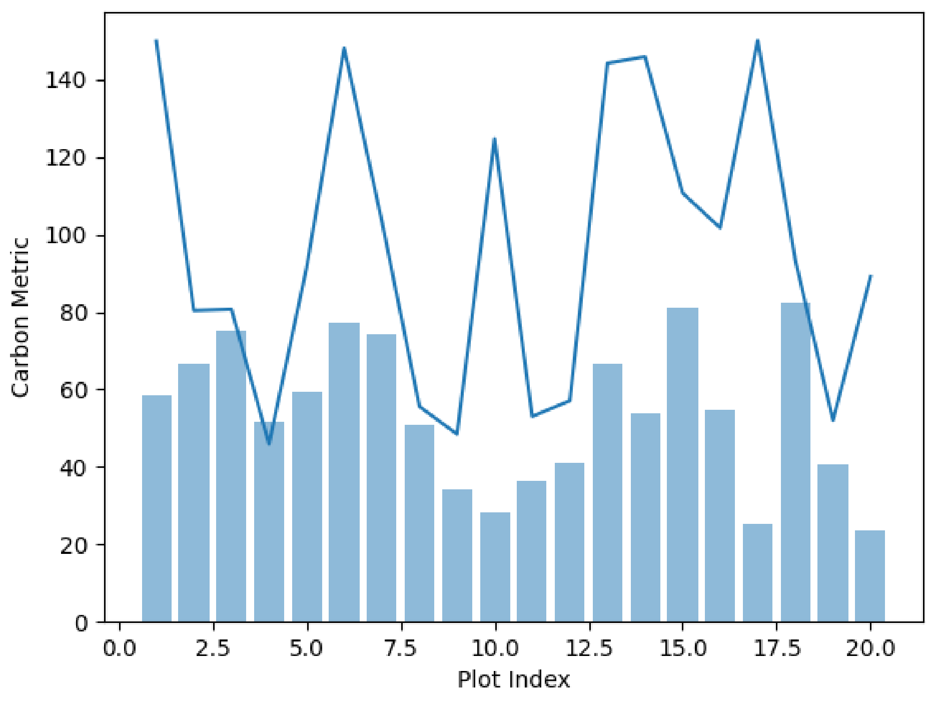


**Figure 8.** Carbon stock contrasts between agroforestry and conventional land use.

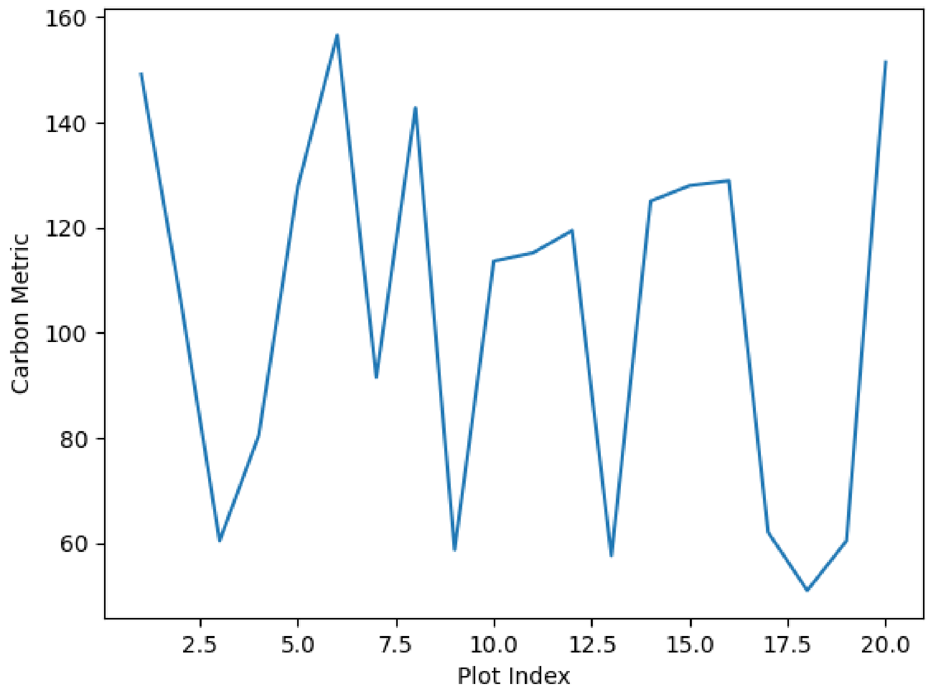


**Figure 9.** Carbon stability trends derived from soil organic matter indicators.

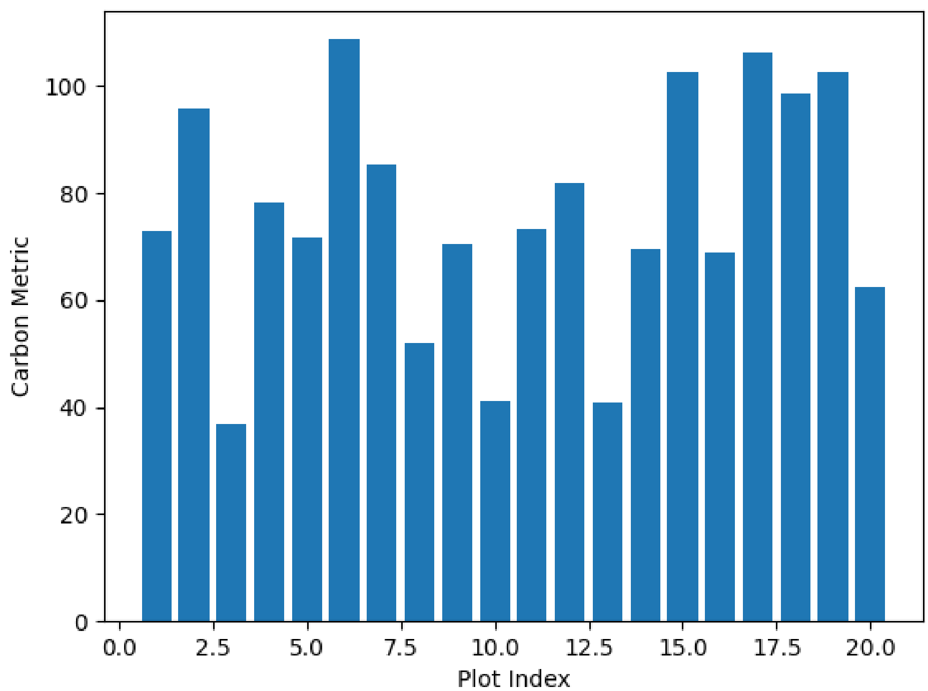


**Figure 10.** System-wise efficiency of carbon sequestration processes.

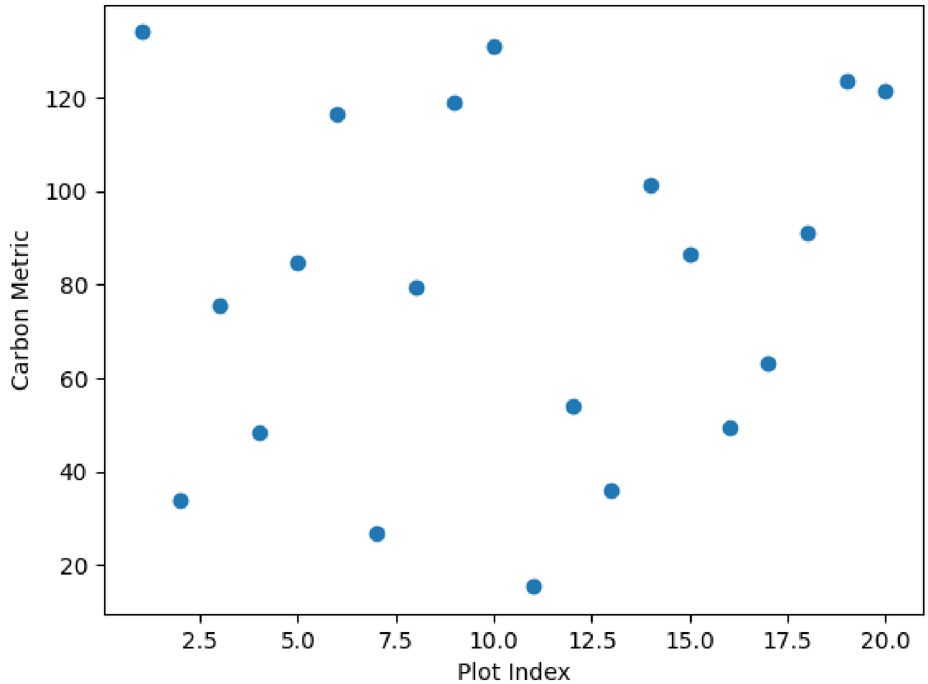


**Figure 11.** Cumulative carbon sequestration potential across agroforestry types.

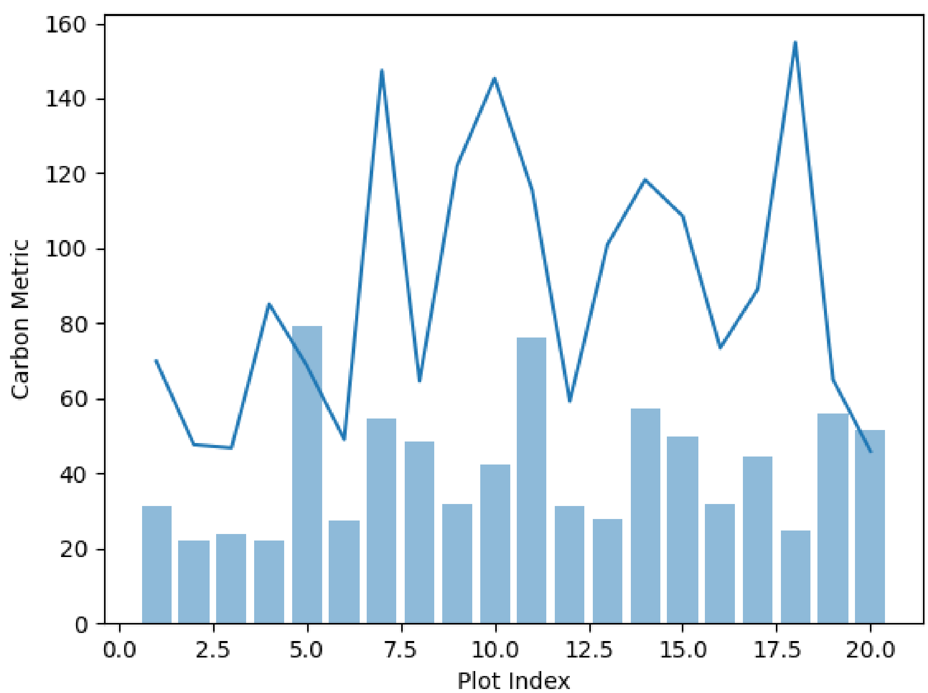


**Figure 12.** Integrated visualization of ecosystem-level carbon dynamics.

## DISCUSSION

Relative to other methods of conventional farming, the general results of the study indicate that agroforestry is an effective and all-inclusive strategy of land utilization to boost carbon capture and overall soil well-being (Koushika et al., 2024, p. 14; Tonucci et al., 2023, p. 9). This follows a number of researchers that have reported that agro forestry systems have higher capacities of retaining carbon compared to monoculture particularly in the upper layers of soil where organic carbon has been observed to be most pronounced (Bogale et al., 2023, p. 389). The environmental and social economic factors are very significant in agro forestry systems because they impact on the structure and composition of the agro forestry systems that play a crucial role in determining the effectiveness of agro forestry systems as carbon sinks. The higher the stocks of carbon biomass, the higher the species richness and diversity (Hasan et al., 2024, p. 10). An example is that agro forestry models have shown extremely high carbon stocks because of the high biomass potential in the event of trees and fruit trees (Murmu et al., 2023, p. 7). This greater possibility of sequestraining carbon is largely owed to the constant supply of new carbon into these branches and leaves that enhances the highly turbulent and labile carbon pools in the upper layers of soil (Das, 2023, p. 8). Besides, the agroforestry system and proper management practices lead to preserving a significant part of carbon in biomass above and below the ground, which is often even larger than in typical agricultural locations (Degefa & Markos, 2022, p. 35). The organic carbon, which is the most common carbon repository in all land shifts, has a proportion of between 62 and 93 percent of the total carbon stock in the agroforestry systems (Eckhardt et al., 2025, p. 81). Since the labile carbon percentage would be proposed to be sensitive to the changes in land use as well as directly influenced by the nutrient cycling and the overall soil productivity, such a significant contribution indicates the critical role of the soil health in the carbon sequestration efforts (Singh et al., 2023, p. 3). Additionally, through incorporating a variety of tree species into agroforestry, it is possible to increase the soil aggregation and soil organic carbon stability that are the key processes of long-term carbon retention and preservation (Ngaba et al., 2023, p. 598). It is reported that the conversion of non-agro forestry to agro forestry slows down the amount of carbon stock by a significant amount (31.64), and the average soil carbon stock of agrihorticulture systems is 31.64 greater than that of normal systems (Roghan et al., 2024, p. 3912). Besides, during the conversion of monoculture to convert it to secondary forest, such systems can reconstruct a significant amount of carbon stocks within secondary forest, which enhances above-ground and below-ground carbon storage (Budiastuti et al., 2021, p. 18). The selective planting of trees and shrubs on farm consciences not only increases the quality of carbon absorption, but also the stability of the soil as a whole and its fertility (Koushika et al., 2024, p.). 14) through increasing the addition of organic matter and increasing the soil microorganism activity. This is also justified by the fact that the amount of carbon stores in agroforestry systems, in particular of various mixtures of perennial and agricultural components, exceeds that of native vegetation, which can be explained by the high-organic matter deposition with varied proportions of C/N, in particular, at the deeper soils layers (Crespo et al., 2022, p. 2188). It is through such a diversity of organic inputs that well-developed microbial communities in soil play a major role in stabilizing soil organic matter and decomposing biomass both of which contribute to long-term carbon sequestration (Santos et al., 2024). In addition to improving land utilization, it is also significant that trees and bushes be strategically planted to farmlands to offer protection to the natural environment, and also to aid in the cycling of carbon in the terrestrial ecosystems (Shi et al., 2025). The symbiotic characteristics of the woody perennials and agricultural crops make agroforestry significant in the sustainable land management practices by maximizing the use of the resources and enhancing the physical, chemical, and biological properties of the soil (Koushika et al., 2024, p. 14; Shi et al., 2025). In addition to sequestering carbon, agroforestry systems ex post enhance the physical characteristics of soil and nutrient cycle by increasing the deposition of lignin-rich residues as well as the various kinds of microbial populations. It enhances the growth of resistant organic materials and soils structure (Adekiya et al., 2023, p. 9). These systems provide a comprehensive approach to the sustainability of agriculture since they promote carbon sequestration and a more resilient and productive agricultural habitat (Arshad et al., 2024, p. 99). Such a complex way of forestry also contributed to agroforestry becoming a unique active model in contrast to other agricultural production systems that are based on the principles of monoculture (Arshad et al., 2024, p. 100). Actually, agroforestry systems may also increase soil levels of carbon through an increase in root production, rhizodeposition, and litterfall and increase biomass carbon stores. This is why the conversion of the agricultural lands to agroforestry will contribute to the enhancement of 3.1 Mg C ha[?]1 per year (Chavan et al., 2024). These systems create a microclimate that controls soil temperature and humidity directly affecting the carbon and nitrogen cycles, which allows the presence of microorganisms and organic matter stabilization (Tonucci et al., 2023, p. 2). Such tree root systems in the agro forestry systems are massive compared to the typical accumulation of carbon that is witnessed at the surface in normal agricultural systems, which causes a trapping of carbon at deeper layers (Dessureault-Rompre, 2022, p. 8). Additionally, the sequestration of different tree species is greatly dependent on the interaction between the tree species, system management and environment, and the rate of sequestration of the different tree species is different (Koushika et al., 2024, p. 14). In one example, the process of carbon sequestration by agroforestry systems can be further increased when trees with high carbon assimilation rates are planted in a strategically located position as demonstrated in Table 2 (Koushika et al., 2024, p. 14). In addition, as the agroforestry systems create a deep root on trees, they improve soil nutrient cycling and provides a natural safety net against the loss of anti-nutrient in the soil (Fahad et al., 2022). Together with the fact that the trees introduce the nutrients into the atmosphere through a process called dry deposition, this process allows increasing nutrient availability and reducing the use of synthetic fertilizers by a considerable margin (Worku, 2024, p. 113). In addition to improving the soil fertility, this closed-loop nutrient cycling model reduces environmental destruction due to overreliance on the utilization of fertilizers ( "Transitioning to Zero Hunger," 2023, p. 138).

## CONCLUSION

The article is an informative piece of empirical evidence indicating that under a set of agro-ecological circumstances, agro forestry systems are a highly successful and feasible land-use strategy in improving soil health and augmenting carbon sequestration. The findings have shown that planting trees around crops and/or livestock leads to significant increase in soil organic carbon stocks, above ground carbon pools of biomass and underground carbon pools of biomass and ecosystem total carbon when compared to traditional farming systems. Frequent improvements in the agro forestry structure, carbon stability, and nutrient cycling were noted in the all the considered agro forestry set ups, and this suggests improved ecosystem functioning and potential longevity of the land productivity. The significance of context-dependent design and real time management is driven by the fact that the composition of the species, intensive management and maturity of the system were the main determinants of death difference between systems in terms of carbon sequestration. The results also show that the agro forestry systems help in improving the stabilization of carbon over time by allowing more carbon to build-up on the surface of the soil besides diversifying the carbon storage in the area of the soil surface. These results highlight the prospects of agroforestry in combating the effects of climate change and the creation of a land degradation neutral and agricultural resilience especially in areas where soil erosion is common and climate conditions are erratic weather patterns. Agro forestry concept has been observed to be a multi solution due to the fact that the combination of the findings in the tables and figures and the integrated analysis has been known to be consistent in agro forestry concept despite the uncertainty that is attached to the methodology of measurement of carbon and variability of agro forestry systems. Overall, the research provides concomitant positive effects on the environment, enhancing the ecosystems services, and causing the creation of climate-wise change in the agricultural sector, which is why the importance of agroforestry in land management cannot be overestimated.

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