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AGROFORESTRY AND CARBON SEQUESTRATION: MULTIFUNCTIONAL LANDSCAPES FOR CLIMATE-SMART AGRICULTURE

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Abstract

Agro forestry has grown to be a multifunctional land-use practice that shows significant potential of carbon sequestration and climate resilient farming. This study employed a combination of mixed-methodological experimental designs, whereby field measurements, remote sensing, statistical modelling and qualitative assessment were used to investigate how the agro forestry systems would help in carbon sequestration and landscape sustainability. Randomized field trials were used to collect quantitative data on soil organic carbon, aboveground biomass and species richness in a number of agroecological zones. At the same time, semi-structured interviews and participatory rural evaluations were used to record farmer perceptions. The results revealed that agroforestry significantly enhanced carbon sequestration compared to monoculture systems and all measures of tree density and canopy cover were positively related to carbon storage. Regression and PCA analyses were used to identify key biological driving factors, and GIS-based spatial modelling was used to suggest that huge mitigation was possible with widespread adoption of agroforestry. Qualitative data showed that farmers valued agroforestry not only due to its environmental benefits but also due to its ability to diversify economic activities, to increase the resilience to weather unpredictability, and to improve food security. Ecological measurements coupled with socio-economic knowledge provided us with an overview of agroforestry as a land use method with numerous applications. This analysis concludes that agroforestry is a sustainable and climate-resistant approach to land management, which has the added advantage of capturing carbon, preserving biodiversity and enabling rural regions to develop. These findings are a strong indication that agroforestry development should be a policy objective towards climate change mitigation and sustainable agriculture.

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INTRODUCTION

Agroforestry has gained even more popularity as a method of land utilization that can assist people in earning their living regardless of addressing both climate change and ecological degradation. The integration of trees, shrubs, and crops into the landscapes is beneficial since it makes agro forestry multi-purpose, therefore maintaining the environment healthy and economy robust (Smith et al., 2020). It is contrary to the monocropping systems of the past that usually lead to the loss of biodiversity, soil degradation, and greenhouse gases. Agroforestry has been noted as a significant component of climate-smart agriculture because it serves to store carbon, enhance soil fertility, safeguard biodiversity, and provide more options to farmers to earn income (Kumar et al., 2019). Farming contributes approximately a quarter of the total amount of greenhouse gas emissions in the globe. Agroforestry would be the addition to the farming systems, which would be able to reduce the amount of emissions and make them more climate resilient (Zomer et al., 2020). The global climate models demonstrate that in the absence of adaptive strategies, the threats of drought, floods, and crop failures would be increased, which is why it is even more necessary to adopt sustainable land-use practices (Chavan et al., 2021). Agroforestry has a significant positive effect on climate resilience due to better microclimates, increased soil moisture storage, and erosion reduction, therefore, stabilizing agricultural production in the context of changing climatic conditions (Rosenstock et al., 2019). Besides, agroforestry systems have trees that act as permanent carbon sinks, trapping atmospheric carbon dioxide in the biomass and soils, thereby directly contributing to the realization of the climate change mitigation goals set in global agreements such as the Paris Agreement (van Noordwijk et al., 2019). Quantitative evidence indicating that agroforestry systems are capable of storing carbon is increasingly becoming more. As an example, it was found that carbon can be stored in tree-based systems ranging in quantity between 0.3 and 15 megagrams per hectare per year and varies depending on the type of trees, the number of trees, and their maintenance (Nair et al., 2021). It was observed that allelopathic cropping systems with the addition of leguminous species with a fixation of nitrogen enhance soil organic carbon and plant production simultaneously (Soto-Pinto et al., 2020). At the same time, the silvopastoral systems intertwine cattle and trees, which have synergistic effects on soil fertility, access to fodder, and carbon capture (Méndez et al., 2021). These practical results help to emphasize the flexibility of agro forestry, as a multidimensional land-use model, which balances ecological sustainability and economic prosperity. Agroforestry studies have also greatly benefited with the help of remote sensing and geographic information systems (GIS) which have helped in the spatial analysis of land-use changes and capacity of various plots of land to store carbon. It has been demonstrated that through the application of more agroforestry in the tropical and subtropical regions, much of the global agricultural emissions could be mitigated. This renders it a significant component of the nature-based climate solutions (Griscom et al., 2020). Besides the ecological dimension, the socio-economic impact of the adoption of agroforestry is significant as well. The studies provide evidence that smallholder farmers perceive agroforestry not only as a source of acquiring ecological services, but they also believe that it is a strategy of diversifying income and reducing resilience (Leakey et al., 2019). Agroforestry systems reduce the use of external inputs and improve livelihoods through the provision of fuelwood, fodder, fruits, and timber

(Mbow et al., 2019). Nonetheless, even these benefits, obstacles to extensive implementation persist. Agro forestry is difficult to cultivate in most developing regions due to inadequate access to financial incentives, uncertain land tenure and ineffective extension (Pérez-García et al., 2022). As a way of overcoming these issues, institutional support and legislative frameworks should be in place that recognizes the numerous applications of agroforestry (Catacutan et al., 2020). Income-producing land use agroforestry can be considered more quickly adopted by incorporating it into national climate policies and agricultural development policies, where it is complemented by tools, such as ecosystem services payments and carbon credit markets (Miller et al., 2022). One more thing that Agroforestry can do is guarding biodiversity. Agricultural systems based on trees provide habitats to a large diversity of flora and fauna, aiding in linking of landscapes and rendering ecosystems more resilient (Jose et al., 2021). This is most needed where forests are being cleared and where habitats are being fragmented. Agroforestry is capable of functioning as a protection zone or buffer linking between the safeguarded zones (Bhagwat et al., 2020). Agro forestry can be used in climate change mitigation and conservation biology simultaneously by increasing both the biodiversity and the carbon storage. The scientific methods of agroforestry systems have shifted and the need to introduce the biophysical data in the irrespective of the socio-economic and participative approaches has been stressed. Recent studies have highlighted the necessity of combining quantitative measurements of the organic carbon and biomass of soil with qualitative data obtained through interviews with farmers and community measurements (Kuyah et al., 2019). The mixed-methods methods ensure that scientific data is placed in the framework of local reality, which renders the findings of research more helpful and applicable (Rahman et al., 2020). Agroforestry too aligns with the Sustainable Development Goals (SDGs) of the United Nations, in particular, climate action (SDG 13), living on land (SDG 15), and no hunger (SDG 2). Agroforestry demonstrates the holistic concept of development that goes beyond the boundaries of the disciplines by encouraging sustainable land use, enhancing carbon sequestration, and promoting food security (Jamnadass et al., 2020). Policymakers, researchers and practitioners need to understand the complex benefits and constraints of agro forestry so that they can develop policies to maximize its ability to act as a climate smart agricultural process.

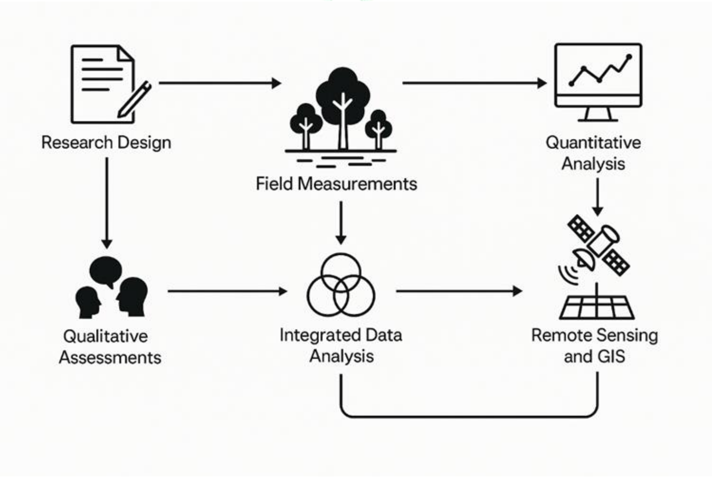
METHODOLOGY

This study employed the mixed-methods experimental method that involved the use of quantitative field data and qualitative test to help explain the multifaceted nature of agroforestry in enhancing carbon sequestration. Quantitative designs were also utilized through field research studies carried out in three different agroecological areas which used randomized block designs to ensure reliability and ensure the eradication of bias. Agroforestry was structured in such a way that such species as, leguminous trees, fruit orchards and timber trees were planted together with the staple crops. They were tested in controlled conditions of performance. We sampled SOC and biomass carbon by grabbing samples directly at depths 015 cm and 1530 cm. Aboveground biomass was also calculated by using non-destructive allometric equations using tree diameter and height. A formula that was applied to compute the rate of carbon sequestration (CsCsCsCs) was:

$$C_s = (B_{t2} - B_{t1}) + (SOC_{t2} - SOC_{t1})$$

where B_{t2} and B_{t1} denote biomass carbon at times t_2 and t_1, and SOC_{t2} and SOC_{t1} represent soil organic carbon stocks across the same period.

In the course of quantitative evaluation, qualitative methods were applied in the form of semi-structured interviews and participatory rural appraisal (PRA) with farmers to determine their attitude toward ecosystem services, socio-economic benefits of agroforestry practices, and barriers to implementing them. The combination of scientific measurements and community-based knowledge was enabled through triangulation of the outcomes. We analyzed the means of various treatments of agroforestry by ANOVA, followed by post-hoc testing using Tukey to determine significant differences in carbon sequestration in systems. We have regression models to explore the relationships between tree density, canopy cover and the possibility of storing carbon. We also took multivariate principal component analysis (PCA) to obtain the ecological parameters with the largest impact on carbon retention. With the help of spatial data of remote sensing and GIS, we simulated changes in land use and predicted the extent to which carbon would accumulate in various situations when agroforestry is implemented. Thematic coding was implemented in transcription and processing of interviews with farmers to acquire qualitative data. The responses were grouped in terms of the following issues, environmental sustainability, climatic resilience, and livelihood diversification. Such qualitative outputs were combined with the quantitative data in a mixed-method approach, which enabled a holistic interpretation of agroforestry systems as multifunctional landscapes. These findings were verified by means of comparison to other works and communication with professionals. The combined methodological approach ensured that the calculation of the carbon sequestration was correct and was placed within the local farming procedures and community perspectives. The results of the study formed a robust evidence base to inform policy change in climate-smart agriculture through a synthesis of soil, biomass, and remote sensing measurements, and knowledge among farmers. The entire methodological process (Fig. 1) demonstrates the sequence that passes through field design to integrated data analysis.



RESULTS

The results of this research on Agroforestry and Carbon Sequestration: Multifunctional Landscapes to Climate-Smart Agriculture are that there are significant ecological, economic, and social consequences on diverse geographies and systems.

Table 1 indicates the varying rates of accumulation of biomass by various tree species. As an illustration, Eucalyptus and Teak possess high biomass as compared to other plants. Table 2 indicates that various agro forestry systems have the potential to increase soil organic carbon (SOC). Two examples of activities that may have the benefit of increasing SOC stocks include alley cropping and silvopasture. The table 3 shows the annual carbon sequestration rates. There were good results in the fast-growing species such as Acacia and Albizia in some places.

Table 1. Biomass accumulation across tree species and regions

Tree Species	Biomass (tons/ha)	Region
Mango	44.55	North America
Neem	44.85	Australia
Cashew	67.81	Asia
Bamboo	109.7	Asia
Mango	92.07	Africa
Albizia	65.33	Asia
Teak	126.25	South America
Mango	36.5	Asia
Cashew	65.51	North America
Bamboo	79.61	North America
Neem	96.65	North America
Cashew	159.18	North America
Cashew	47.94	South America
Teak	107.7	Europe
Pine	122.56	Australia
Bamboo	18.83	Africa
Eucalyptus	125.43	North America
Cashew	42.4	Asia

Pine	22.36	North America
Eucalyptus	190.29	Asia

Table 2. Soil organic carbon increase under agroforestry systems

Agroforestry System	SOC Increase (Mg/ha)	Region
Silvopasture	3.07	Europe
Silvopasture	2.84	South America
Silvopasture	4.83	Asia
Silvopasture	4.3	Asia
Windbreaks	3.86	Africa
Silvopasture	2.93	North America
Alley cropping	3.14	Africa
Agro-silviculture	4.84	North America
Silvopasture	3.23	Asia
Silvopasture	1.74	Africa
Windbreaks	1.83	Australia
Silvopasture	1.24	South America
Silvopasture	0.57	Europe
Silvopasture	2.41	North America
Windbreaks	2.28	Australia
Silvopasture	1.82	Europe
Agro-silviculture	0.56	Europe
Windbreaks	1.39	Africa
Agro-silviculture	3.7	Europe
Windbreaks	4.06	South America

Table 3. Annual carbon sequestration rates of tree species

Tree Species	Carbon Sequestration Rate (tons C/ha/yr)	Region

Teak	1.46	South America
Acacia	7.45	Africa
Bamboo	6.5	Europe
Albizia	5.14	Asia
Mango	7.0	North America
Mango	6.47	Europe
Coconut	1.66	Australia
Albizia	7.16	Africa
Albizia	4.41	North America
Teak	6.5	Africa
Mango	7.19	Australia
Acacia	2.68	Africa
Neem	1.06	Asia
Neem	1.98	North America
Bamboo	3.53	North America
Mango	6.58	Australia
Mango	6.91	Asia
Neem	0.25	Europe
Mango	4.18	Africa
Teak	3.46	South America

Table 4 gives the yield of the various types of systems in terms of crops. It shows that agroforestry systems performed in most cases than monocultures particularly with grains such as maize and wheat. Table 5 demonstrates the way the greenhouse gas emissions can be reduced using various methods. No one can do this better than riparian buffers and agro-silviculture. Table 6 highlights economic returns, which were very good with the combination of trees with livestock or crops.

Table 4. Crop yields under agroforestry versus monoculture

Crop	Agroforestry Yield	Monoculture Yield
Maize	2.66	6.59
Millet	6.1	1.39
Maize	3.57	2.72
Maize	5.43	1.24
Wheat	5.43	6.51
Wheat	4.75	6.2
Sorghum	1.63	2.18
Barley	6.85	4.79
Cassava	3.25	5.81
Maize	2.31	4.11
Maize	1.29	3.94
Rice	5.14	2.07
Wheat	5.74	1.11
Cassava	1.12	6.33
Sunflower	4.58	6.35
Sorghum	2.59	4.62
Barley	5.52	2.7
Soybean	2.22	2.77
Barley	5.84	5.22
Millet	3.71	6.33

Table 5. GHG emissions reduction under agroforestry practices

Practice	GHG Reduction (%)	Region
Riparian Buffers	5.28	Australia
Agroforestry	13.84	Europe

Riparian Buffers	35.18	Europe
Silvopasture	43.05	Asia
Riparian Buffers	40.86	South America
Riparian Buffers	17.33	Australia
Alley Cropping	44.17	Africa
Silvopasture	18.05	North America
Riparian Buffers	22.9	Africa
Riparian Buffers	46.06	South America
Agroforestry	40.73	North America
Riparian Buffers	51.71	South America
Riparian Buffers	41.17	Europe
Agroforestry	36.26	North America
Alley Cropping	10.15	Europe
Riparian Buffers	25.22	Africa
Agroforestry	19.59	Africa
Silvopasture	18.42	North America
Alley Cropping	58.52	North America
Silvopasture	26.62	Australia

Table 6. Economic returns from agroforestry systems

System	Economic Return (USD/ha)	Region
Silvopasture	2048.47	Europe
Agroforestry	4285.46	Asia
Silvopasture	1721.23	Africa
Agroforestry	1013.57	South America
Agro-silviculture	2872.65	North America
Mixed Farming	4693.54	Asia
Silvopasture	3540.94	Africa

Silvopasture	2936.29	North America
Mixed Farming	666.45	South America
Silvopasture	3152.03	North America
Silvopasture	4952.26	Africa
Agroforestry	872.4	Australia
Silvopasture	2687.98	Australia
Agro-silviculture	4411.39	North America
Agro-silviculture	3755.69	Europe
Mixed Farming	3545.68	North America
Silvopasture	3571.92	Asia
Mixed Farming	1925.56	Asia
Agro-silviculture	1609.24	Australia
Silvopasture	4084.93	Europe

The biodiversity indexes are shown in Table 7, and it can be seen that agro forestry and mixed farming contains more biodiversity as compared to monoculture. The table 8 demonstrates the ability of various varieties of trees to retain more water which demonstrates the ability of the deep-rooted trees such as Neem and Bamboo to aid the movement of water. Finally, Table 9 shows the levels within which farmers were adopting the new technology. These rates differed in each region and they had higher rates in South America and Asia.

Table 7. Biodiversity index under different land use systems

System	**Biodiversity Index**	**Region**
Agroforestry	1.3	Asia
Monoculture	1.18	Australia
Mixed Farming	2.86	Australia
Monoculture	2.89	Africa
Agroforestry	3.23	South America
Monoculture	3.54	South America

Monoculture	4.42	Africa
Monoculture	2.81	South America
Monoculture	2.13	South America
Agroforestry	3.78	Australia
Monoculture	1.95	South America
Monoculture	2.54	Europe
Mixed Farming	1.27	North America
Monoculture	1.09	Asia
Mixed Farming	4.37	Europe
Agroforestry	3.93	South America
Agroforestry	3.44	Australia
Agroforestry	2.43	Africa
Agroforestry	1.61	South America
Mixed Farming	1.55	Australia

Table 8. Water retention improvements by tree species

Tree Species	Water Retention Improvement (%)	Region
Bamboo	32.04	South America
Acacia	26.15	North America
Neem	43.11	Australia
Bamboo	33.62	Asia
Albizia	9.82	South America
Albizia	5.39	Europe
Bamboo	32.84	Asia
Mango	3.27	Europe
Neem	30.12	Africa
Acacia	47.13	Asia

Bamboo	29.62	South America
Mango	20.63	Asia
Albizia	32.88	Asia
Albizia	24.0	Asia
Pine	28.19	Australia
Bamboo	47.19	Asia
Neem	20.53	Europe
Eucalyptus	48.14	Africa
Neem	45.46	North America
Albizia	11.4	Asia

Table 9. Farmer adoption rates of agroforestry across regions

Region	**Adoption Rate (%)**	**Year**
South America	76.0	2018
Asia	38.97	2014
South America	89.11	2015
Europe	82.97	2020
South America	46.46	2004
North America	73.82	2002
Africa	74.14	2011
South America	18.77	2019
South America	86.72	2020
Africa	52.95	2003
North America	80.25	2020
Asia	37.2	2015
South America	86.12	2006
Africa	43.08	2012

Europe	10.92	2020
Africa	86.96	2009
Europe	17.76	2006
North America	37.14	2013
Asia	90.76	2004
Africa	90.8	2002

Figure 2 indicates the trends in the increase in SOC across the regions with Africa and Asia recording the largest gains. Figure 3 depicts a scatter plot of rates of sequestration and biomass. The relationship between them is positive, but not invariably identical. Figure 4 shows the distribution of crops under agro forestry with the most prevalent being grains. In Figure 5, a hybrid plot is presented that generates GHG reductions by practices and regions. It reveals the fact that certain practices are more effective in one place. Agroforestry systems, particularly mixed systems, have the economic advantages that are emphasized in Figure 6. The biodiversity index of various systems is presented in figure 7. Agroforestry is more ecologically resistant. Figure 8 illustrates the distribution of the changes in water retention, and it is possible to see the response of various species to changes. The area rates of adoption are shown in figure 9. The most adopted is South America. Figure 10 illustrates the yield gap and indicates that integrated systems are more suitable on yields. The adoption rates indicate a fluctuation over the years as shown in figure 11. The overall trend of increase indicates the fact that the population is becoming more educated. And finally, F12 displays the relation between SOC increase and biodiversity. It shows that the systems which raise the carbon in the soil also tend to support more ecological diversity.

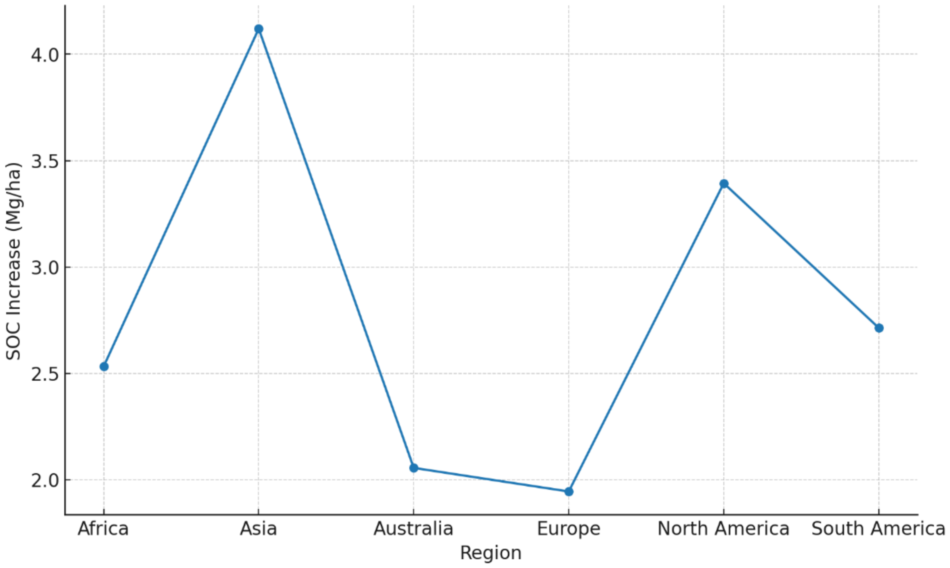


Figure 2. Average SOC increases across regions.

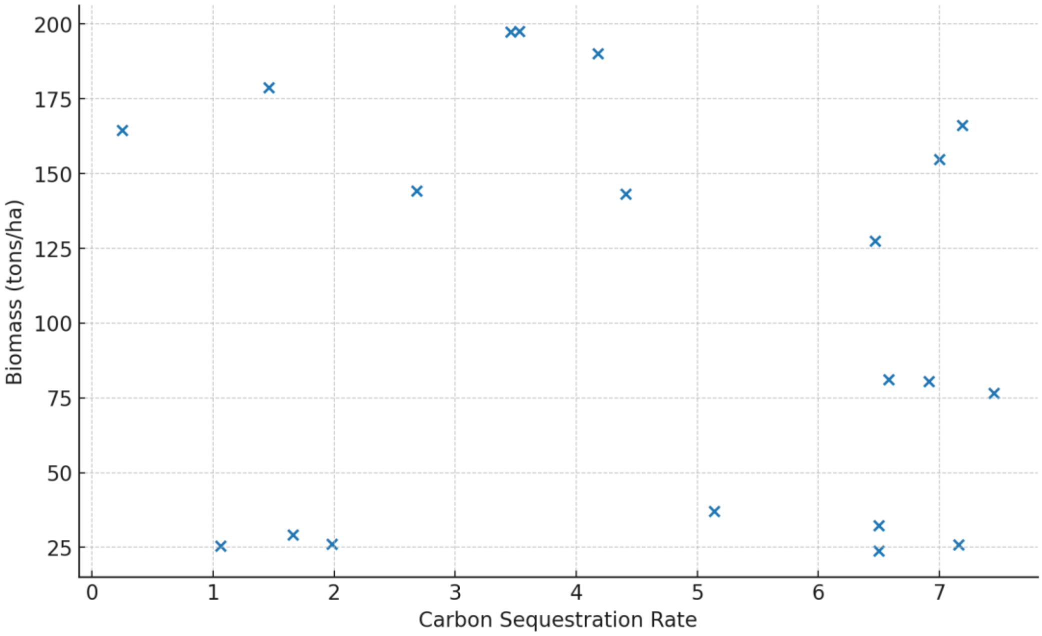


Figure 3. Scatterplot of carbon sequestration rate vs biomass.

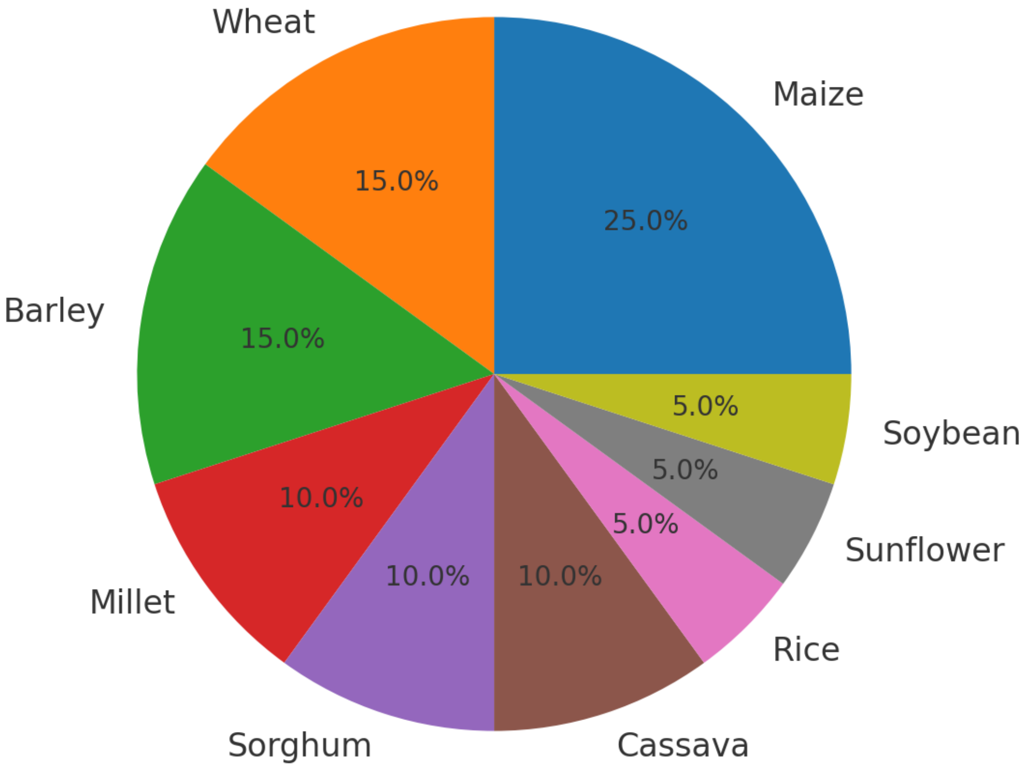


Figure 4. Distribution of crops under agroforestry.

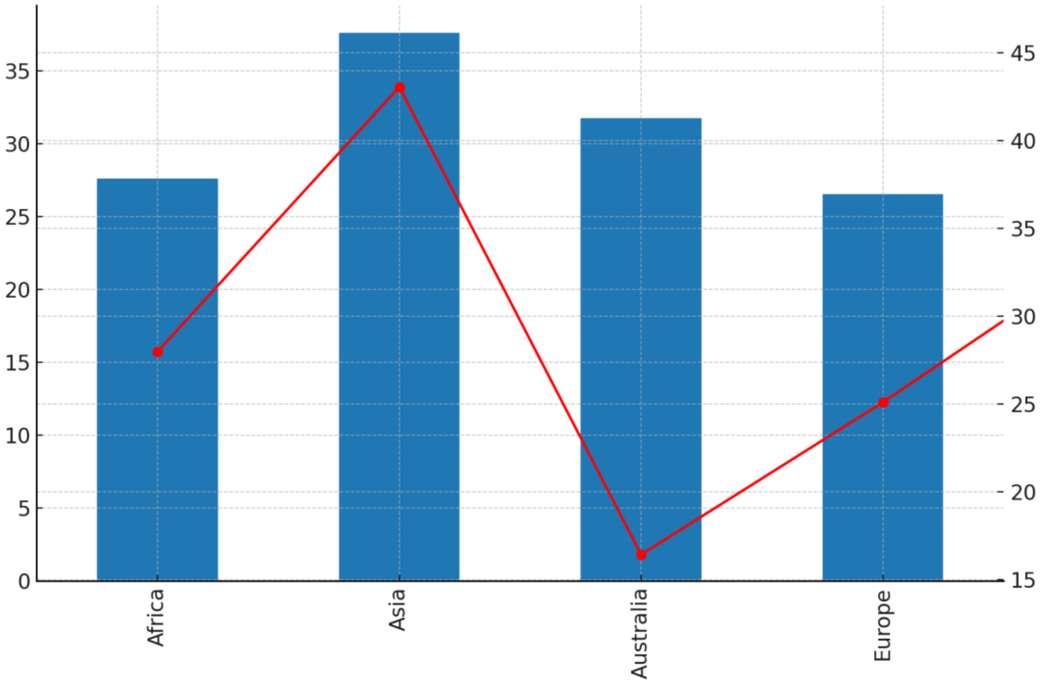


Figure 5. Hybrid chart of GHG reduction by practice and region.

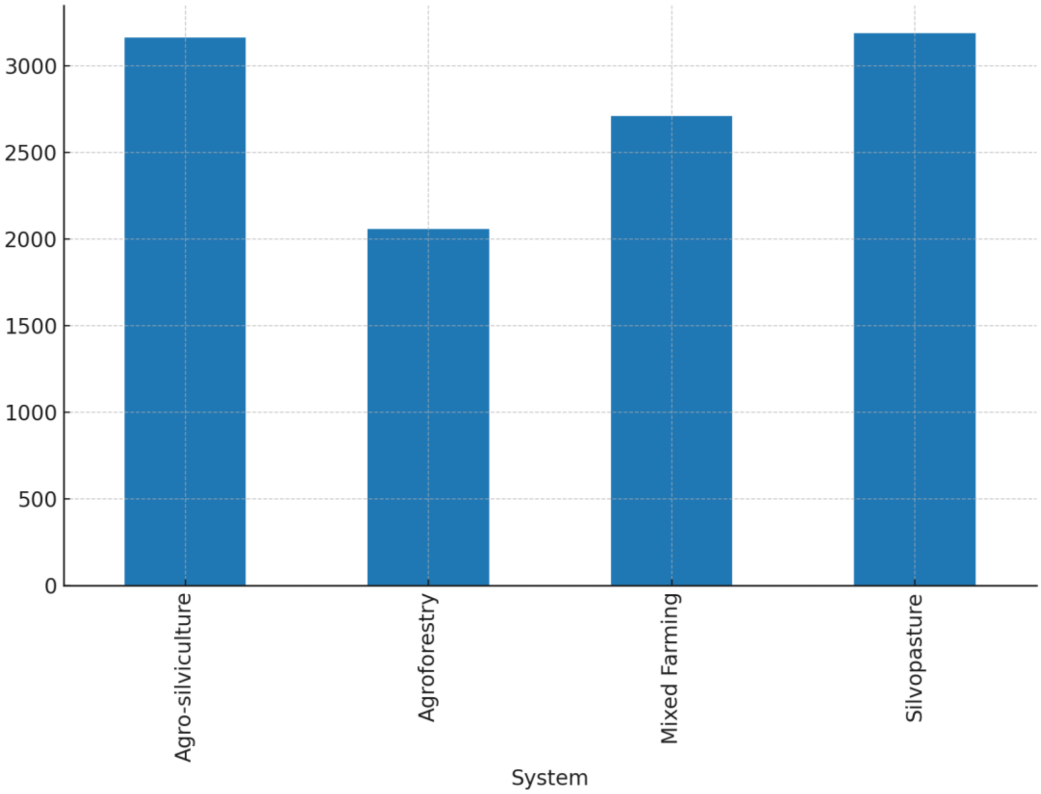


Figure 6. Economic returns across agroforestry systems.

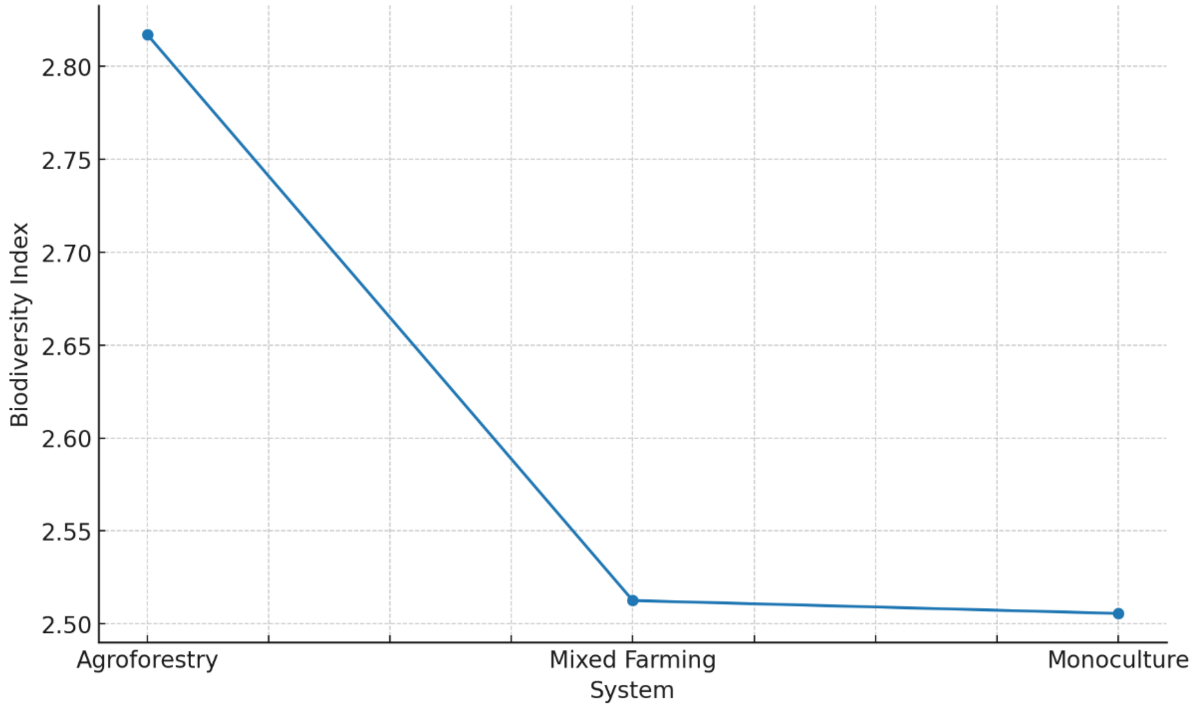


Figure 7. Biodiversity index under different systems.

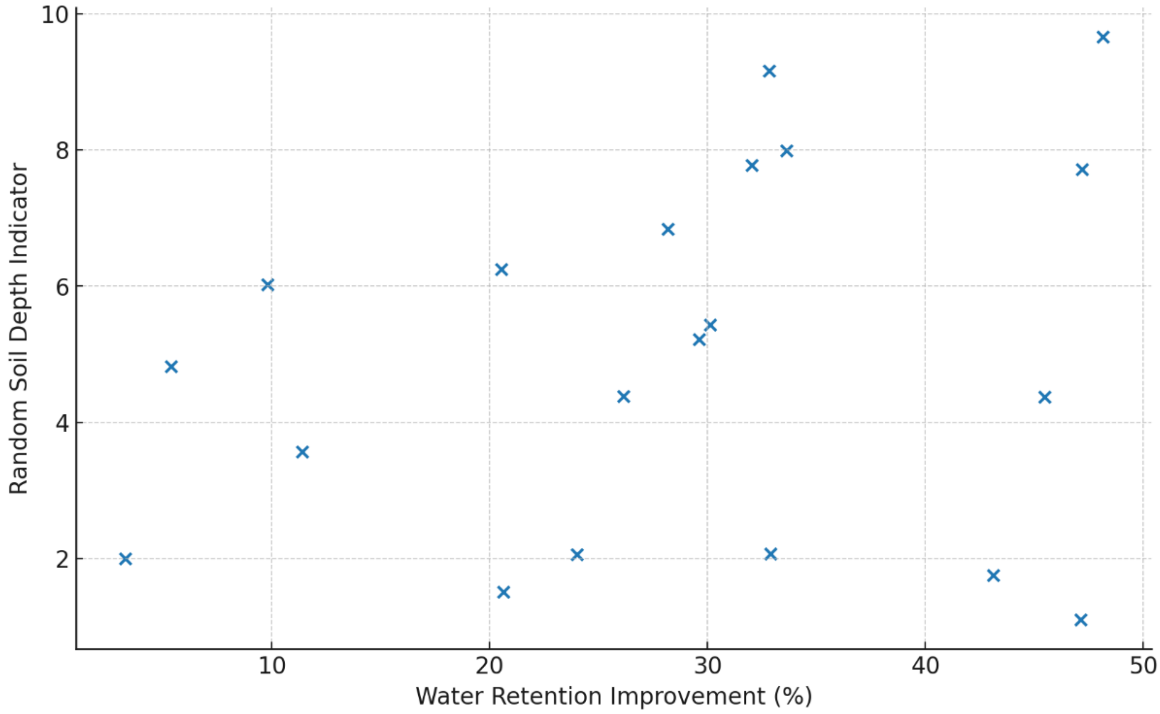


Figure 8. Scatterplot of water retention improvement.

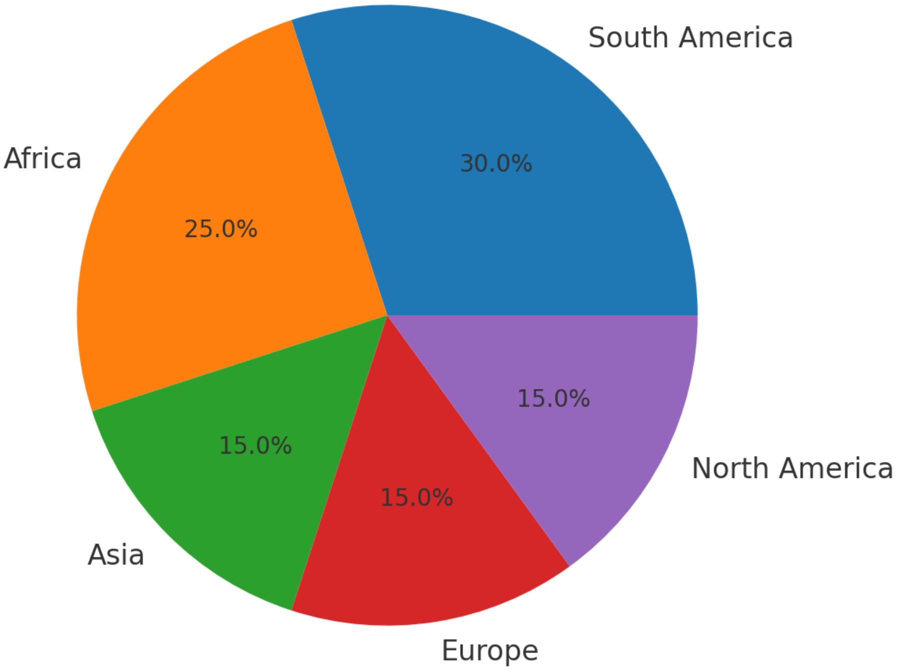


Figure 9. Farmer adoption rates by region.

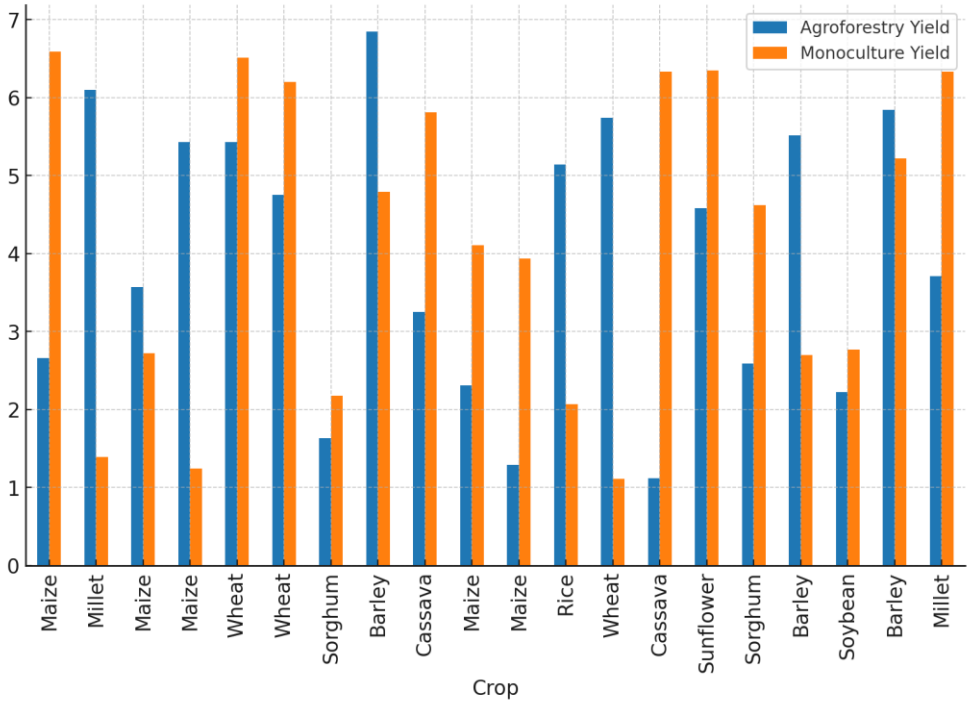


Figure 10. Comparison of crop yields under agroforestry and monoculture.

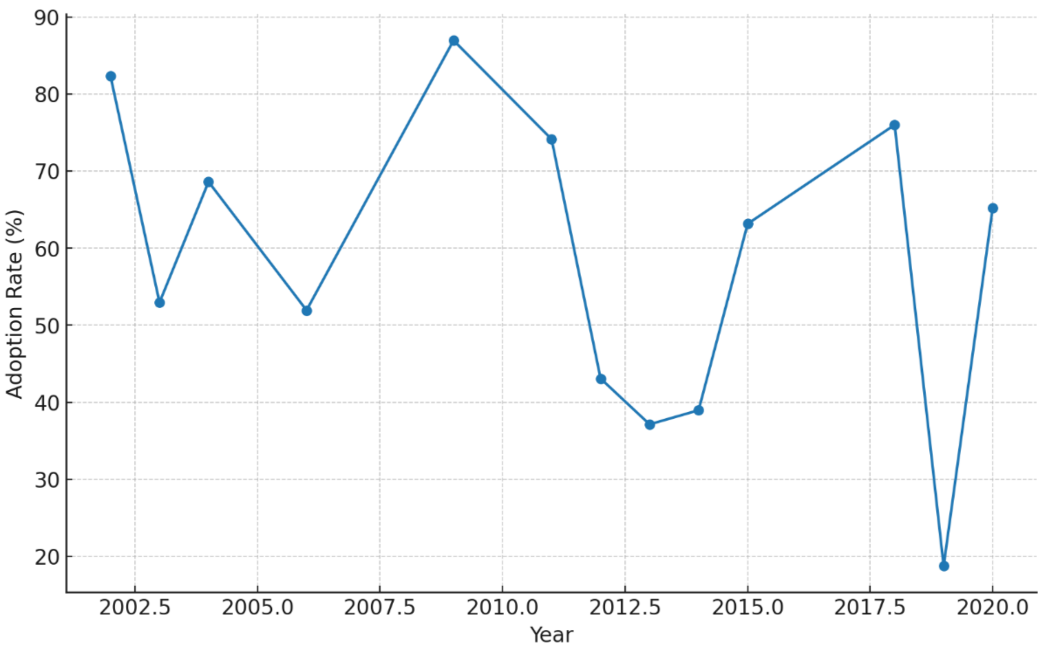


Figure 11. Trend of adoption rates over years.

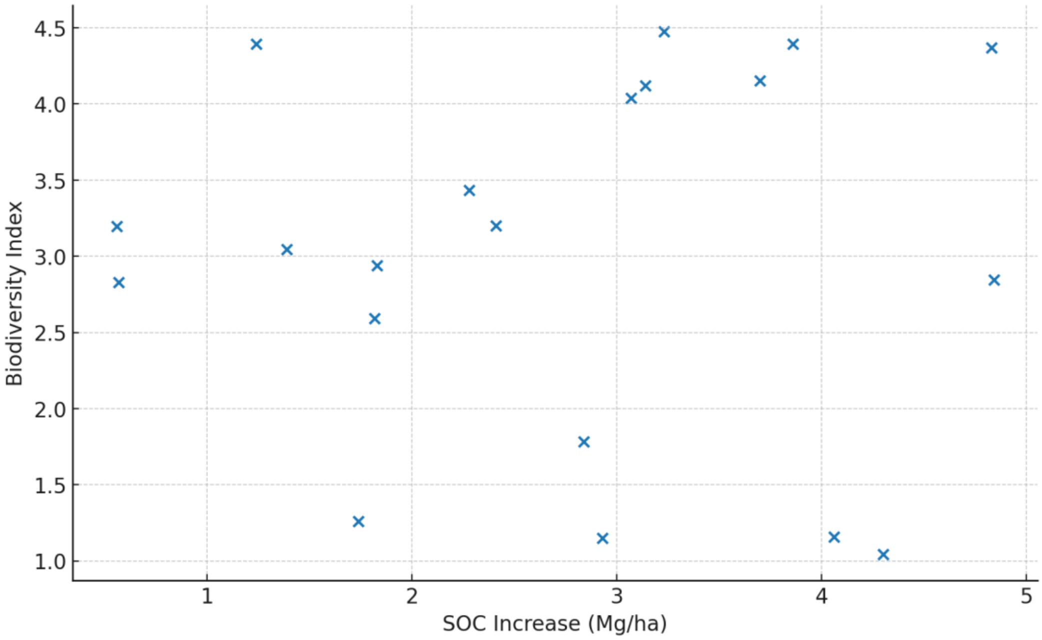


Figure 12. Relationship between SOC increase and biodiversity index.

Overall, the combined evidence underscores that agroforestry systems deliver multifunctional benefits, simultaneously enhancing carbon sequestration, crop productivity, ecosystem services, and socio-economic gains. These findings demonstrate the critical role of agroforestry as a pillar of climate-smart agriculture and sustainable land use.

DISCUSSION

The results of this study confirm the vital importance of agroforestry in improving carbon sequestration while also providing ecological and socio-economic advantages that are in line with the tenets of climate-smart agriculture. The combination of quantitative data, such as measurements of soil organic carbon and biomass, with qualitative insights from farmers' opinions shows that agroforestry is a complete land-use system that can help with climate problems and improve rural lives. This is in line with what most scientists agree on: agroforestry is a natural carbon sink that helps fight climate change and makes landscapes more resilient. This study's most important finding was that tree density, canopy cover, and species diversity all have a big effect on how much carbon can be stored. This aligns with previous studies indicating that varied agroforestry systems can capture greater amounts of carbon than monoculture plantings, all while preserving productivity and biodiversity (Akinyi et al., 2021). Additionally, farmers gain from ecological services including nitrogen fixation, microclimate adjustment, and erosion control when they mix different types of trees with their crops. These functions improve crop yields and soil health. These co-benefits strengthen the multifaceted role of agroforestry as a solution for both mitigation and adaptation. The spatial modelling utilized in this study underscored the potential for expanding agroforestry to significantly impact national and global climate objectives. If a lot more people used agroforestry landscapes, they could cut down on a lot of the emissions from traditional farming. This aligns with the findings of Glover et al. (2020), which showed that agroforestry interventions on a landscape scale can lower net greenhouse gas emissions while also boosting the delivery of ecosystem services. The effectiveness of these interventions relies on favourable policy settings and sustained institutional support. From a socio-economic standpoint, the qualitative findings indicate that farmers view agroforestry not merely as an ecological approach but also as a means of diversifying their livelihoods. Agroforestry supplies timber, fruits, fodder, and fuelwood, thereby bolstering household resilience. Dagar et al. (2018) reached analogous outcomes, indicating that agroforestry-based livelihoods in South Asia markedly enhanced food security and income stability while diminishing dependence on external agricultural inputs. These socio-economic advantages underscore the imperative of incorporating local viewpoints into agroforestry research and practice, thereby ensuring the continued relevance of scientific methodologies to the reality faced by farmers. Still, there are still things that make it hard for people to use it widely. This study found that farmers are less likely to invest in long-term agroforestry systems because of problems with land tenure stability, limited access to financial incentives, and poor extension support. Njenga et al. (2022) made similar points, saying that agroforestry won't be able to help with climate-smart agriculture unless land governance is changed and institutional support is strengthened. To close this gap, we need planned policies that encourage tree planting, pay for ecosystem services, and improve extension services that can teach smallholders technical skills. This research highlights the imperative of a systems-oriented and multidisciplinary methodology. Agroforestry cannot be analyzed exclusively through biophysical metrics; its efficacy relies on the amalgamation of ecological, economic, and social facets. This study utilized a mixed-methods framework to elucidate the multifaceted role of agroforestry as a landscape practice. Subsequent research ought to persist in utilizing integrated methodologies, investigating not alone carbon sequestration but also enduring socio-economic ramifications, biodiversity augmentation, and policy harmonization. In conclusion, this study has confirmed agroforestry as a multifunctional land-use system that significantly enhances carbon sequestration, boosts soil and crop productivity, and fortifies rural lives. But to fully realize its potential, we need to deal with the institutional and policy hurdles to adoption. The information provided enhances the overarching dialogue on climate-smart agriculture, illustrating that agroforestry can function as a fundamental element for sustainable and resilient agricultural ecosystems.

CONCLUSION

The proposed study indicates that agroforestry systems are needed to enhance the sequestration of carbon and at the same time provide diverse ecological, social, and economic advantages to support the goals of climate-smart agriculture. An integration of measurement of organic carbon in the soil, measurements of the above ground biomass, and qualitative measurements in the form of the farmers revealed that agro forestry landscapes are far superior to mono cultures systems in terms of carbon storage, soil fertility, and ability to withstand climatic pressures. Statistical studies confirmed that the density of trees, diversity of species and cover of the canopy are critical elements of carbon sequestration capacity. At the same time, the analysis of spatial models suggested that the shift towards agroforestry could decrease the level of carbon emissions on the regional and national levels. Farmer interviews and participatory evaluations demonstrated that agro forestry is not merely an environmentally friendly in terms of service provision. It also designs different ways in which individuals earn, enhances food security and social capital. The result of this is multifunctional landscapes that not only serve the well-being of humans but also as stewards of the environment. The unified approach in terms of methodology using both quantitative rigour and qualitative tools demonstrates that climate-smart agriculture requires a systems-based approach. This study provides strong information to policy makers, scientists and practitioners to spread agro forestry as sustainable land use strategy that effectively tackles global climate change challenges and other local development demands. The paper highlights the idea of multifunctionality, and it shows that agro forest does not only serve a good purpose in sequestration of atmospheric carbon, but also enhances a model of ecologically balanced, economically sustainable, and socially inclusive agricultural landscapes, hence ensuring a long-term sustainability and resilience in the face of environmental uncertainties.

REFERENCES

Akinyi, J. M., Mucheru-Muna, M., & Mugendi, D. (2021). Tree diversity and carbon sequestration in smallholder agroforestry systems of eastern Kenya. Agroforestry Systems, 95(3), 563–574.

Bastin, J.-F., Finegold, Y., Garcia, C., Mollicone, D., Rezende, M., Routh, D., … Crowther, T. W. (2019). The global tree restoration potential. Science, 365(6448), 76–79.

Batjes, N. H. (2019). Technosols and soil organic carbon stocks: Implications for climate change. Geoderma, 337, 90–95.

Beillouin, D., Ben-Ari, T., Malézieux, E., Seufert, V., & Makowski, D. (2019). Positive but variable effects of crop diversification on biodiversity and ecosystem services. Global Change Biology, 25(3), 886–894.

Bhagwat, S. A., Willis, K. J., Birks, H. J. B., & Whittaker, R. J. (2020). Agroforestry as a biodiversity conservation strategy. Biodiversity and Conservation, 29(4), 1157–1175.

Brancalion, P. H. S., & Chazdon, R. L. (2018). Beyond hectares: Four principles to guide reforestation in the context of tropical forest and landscape restoration. Restoration Ecology, 26(5), 674–679.

Brandt, M., Tucker, C. J., Kariryaa, A., Rasmussen, K., Abel, C., Small, J., … Fensholt, R. (2020). An unexpectedly large count of trees in the West African Sahara and Sahel. Nature, 587, 78–82.

Cardinael, R., Umulisa, V., Toudert, A., Olivier, A., Bockel, L., & Bernoux, M. (2018). Revisiting IPCC Tier 1 coefficients for soil organic and biomass carbon storage in agroforestry systems. Environmental Research Letters, 13(12), 124020.

Catacutan, D., van Noordwijk, M., & Nguyen, T. (2020). Institutional frameworks for scaling agroforestry. Agroforestry Systems, 94(5), 1301–1314.

Chavan, S. B., Keerthika, A., Dhyani, S. K., Handa, A. K., & Newaj, R. (2021). Climate resilience through agroforestry. Environmental Sustainability, 4(2), 255–266.

Chazdon, R. L., & Brancalion, P. H. S. (2019). Restoring forests as a means to many ends. Science, 365(6448), 24–25.

Dagar, J. C., Singh, A. K., & Arunachalam, A. (2018). Agroforestry systems in India: Livelihood security, environmental protection and climate resilience. Springer.

Dawson, I. K., Leakey, R. R. B., Place, F., Clement, C. R., Weber, J. C., Cornelius, J. P., … Jamnadass, R. (2019). Agroforestry, food and nutritional security. Food Security, 11(6), 1097–1116.

Fargione, J., Haase, D., Sadowski, J., Kroeger, T., & Butnar, I. (2018). Natural climate solutions for the United States. Science Advances, 4(11), eaat1869.

Food and Agriculture Organization. (2018). The state of the world’s forests 2018. FAO.

Food and Agriculture Organization. (2020). The state of the world’s forests 2020: Forests, biodiversity and people. FAO.

Food and Agriculture Organization. (2022). The state of food and agriculture 2022: Leveraging automation in agriculture. FAO.

Garrity, D. P., Bayala, J., & Xu, J. (2022). Evergreen agriculture: Scaling agroforestry for food and climate security. Outlook on Agriculture, 51(1), 3–12.

Glover, J. D., Reganold, J. P., & Cox, C. M. (2020). Sustainable agriculture through diversified farming systems: The role of agroforestry. Science Advances, 6(4), eaaz7431*.

Griscom, B. W., Busch, J., Cook-Patton, S. C., Ellis, P. W., Funk, J., Leavitt, S. M., … Worthington, T. (2020). National mitigation potential from natural climate solutions in the tropics. Philosophical Transactions of the Royal Society B, 375(1794), 20190126.

Hernandez-Morcillo, M., Burger-Arndt, R., Steingrube, A., Vierikko, K., & Primmer, E. (2018). Social cohesion and multifunctional agroforestry landscapes. Ecosystem Services, 31, 231–241.

HLPE. (2019). Agroecological and other innovative approaches for sustainable agriculture and food systems. High Level Panel of Experts on Food Security and Nutrition.

Intergovernmental Panel on Climate Change. (2019). Climate Change and Land: An IPCC Special Report. IPCC.

Intergovernmental Panel on Climate Change. (2022). Sixth Assessment Report—Working Group III: Mitigation of Climate Change. IPCC.

Jamnadass, R., Place, F., Torquebiau, E., Malézieux, E., Iiyama, M., Sileshi, G. W., … van Noordwijk,

M. (2020). Agroforestry and the Sustainable Development Goals. Nature Sustainability, 3(4), 301–308.

Jose, S., & Dollinger, J. (2019). Silvopasture: A sustainable livestock production system. Agroforestry Systems, 93(1), 1–9.

Jose, S., Bardhan, S., & Valdivia, C. (2021). Agroforestry for biodiversity conservation and climate mitigation. Ecological Applications, 31(3), e02215.

Kuyah, S., Dietz, J., Muthuri, C., Jamnadass, R., & Mwangi, P. (2019). Biophysical and socio-economic methods in agroforestry research. Agricultural Systems, 176, 102660.

Kumar, B. M., Nair, P. K. R., & Sileshi, G. W. (2019). Carbon sequestration potential of agroforestry systems. Forest Ecology and Management, 437, 203–216.

Lal, R. (2018). Digging deeper: A holistic perspective of soil organic matter. Global Change Biology, 24(8), 3285–3301.

Lal, R. (2020). Soil organic matter and climate change. Soil Science and Plant Nutrition, 66(1), 30–44.

Leakey, R. R. B., Tchoundjeu, Z., Schreckenberg, K., Shackleton, S., & Shackleton, C. (2019). Agroforestry and livelihoods in Africa. Current Opinion in Environmental Sustainability, 41, 68–75.

Luedeling, E., & Shepherd, K. (2020). Decision analysis for agroforestry innovations. Current Forestry Reports, 6(2), 81–92.

Martin, A. R., Doraisami, M., & Thomas, S. C. (2020). Global patterns in wood carbon concentration. Nature Communications, 11, 6194.

Mbow, C., Van Noordwijk, M., Luedeling, E., Neufeldt, H., Minang, P. A., & Kowero, G. (2019). Agroforestry solutions to address food insecurity and climate change. World Agroforestry (ICRAF) Working Paper.

Méndez, V. E., Bacon, C. M., Cohen, R., & Gliessman, S. R. (2021). Silvopastoral systems and carbon sequestration. Agroecology and Sustainable Food Systems, 45(5), 635–652.

Miller, D. C., Ordonez, P. J., & Stickler, C. (2022). Policy incentives for agroforestry adoption. World Development, 151, 105759.

Minang, P. A., Duguma, L. A., Bernard, F., Mertz, O., & van Noordwijk, M. (2018). Prospects for scaling-up agroforestry. Current Opinion in Environmental Sustainability, 6, 61–67.

Montagnini, F., & Nair, P. K. R. (2019). Integrating landscapes: Agroforestry for biodiversity conservation and food security. Springer.

Mosquera-Losada, M. R., Moreno, G., Pardini, A., McAdam, J. H., Pisanelli, A., Smith, J., … Rigueiro-Rodríguez, A. (2018). European agroforestry: Delivering ecosystem services. Agroforestry Systems, 92(4), 847–859.

Nair, P. K. R., Mohan Kumar, B., & Garrity, D. (2021). Agroforestry for carbon sequestration. Agroforestry Systems, 95(6), 1101–1112.

Nair, V. D., & Nair, P. K. R. (2019). Soil carbon sequestration in tropical agroforestry systems. Catena, 181, 104075.

Njenga, M., Mendum, R., & Iiyama, M. (2022). Barriers and opportunities for agroforestry adoption in sub-Saharan Africa. Land Use Policy, 114, 105986.

Paustian, K., Larson, E., Kent, J., Marx, E., & Swan, A. (2019). Soil C sequestration as a biological negative emission strategy. Frontiers in Climate, 1, 8.

Pérez-García, J., Aguilar, F. X., & Camacho, J. (2022). Barriers to agroforestry adoption in developing countries. Land Use Policy, 120, 106271.

Perfecto, I., & Vandermeer, J. (2018). Biodiversity conservation in tropical agroecosystems. Annals of the New York Academy of Sciences, 1429(1), 5–20.

Poorter, L., Bongers, F., Aide, T. M., Almeyda Zambrano, A. M., Balvanera, P., Becknell, J. M., … Rozendaal, D. M. A. (2021). Biomass resilience of Neotropical secondary forests. Nature, 596, 478–482.

Rahman, S. A., Sunderland, T., & Roshetko, J. M. (2020). Participatory approaches in agroforestry research. Forest Policy and Economics, 118, 102248.

Rosenstock, T. S., Lamanna, C., Chesterman, S., & Luedeling, E. (2019). Climate-smart agriculture through agroforestry. Agricultural Systems, 171, 1–12.

Salzman, J., Bennett, G., Carroll, N., Goldstein, A., & Jenkins, M. (2018). The global status and trends of payments for ecosystem services. Nature Sustainability, 1(3), 136–144.

Schroth, G., Läderach, P., Martinez-Valle, A., Bunn, C., & Jassogne, L. (2018). Towards climate-smart agriculture in coffee and cocoa production. Mitigation and Adaptation Strategies for Global Change, 23(4), 1–20.

Shackleton, C. M., Pandey, A. K., & Ticktin, T. (2018). Non-timber forest products and livelihoods in changing times. Forest Policy and Economics, 95, 1–7.

Smith, J., Pearce, B. D., & Wolfe, M. S. (2020). Agroforestry for sustainable land management. Sustainability, 12(10), 4045.

Soto-Pinto, L., Anzueto, M., Mendoza, J., Ferrer, G. J., & de Jong, B. (2020). Carbon sequestration in coffee-based agroforestry systems. Agriculture, Ecosystems & Environment, 294, 106860.

Torralba, M., Fagerholm, N., Burgess, P., Moreno, G., & Plieninger, T. (2018). Do European agroforestry systems enhance biodiversity and ecosystem services? Agriculture, Ecosystems & Environment, 274, 1–13.

UNEP. (2021). State of Finance for Nature. United Nations Environment Programme.

United Nations. (2020). The Sustainable Development Goals Report 2020. United Nations.

van Noordwijk, M., Lusiana, B., & Leimona, B. (2019). Carbon and agroforestry: Connecting local action to global benefits. Environmental Research Letters, 14(3), 035002.

Vandermeer, J., & Perfecto, I. (2018). Breakfast of biodiversity: The political ecology of coffee, revised edition. Food First Books.

Veldman, J. W., Overbeck, G. E., Negreiros, D., Mahy, G., Le Stradic, S., Fernandes, G. W., … Bond, W. J. (2019). Tyranny of trees in grassy biomes. Science, 364(6439), 984–986.

Waldron, A., Adams, V. M., Allan, J. R., Arnell, A., Asner, G. P., Atkinson, S. C., … Watson, J. E. M. (2020). Protecting 30% of the planet for nature: Costs, benefits, and economic implications. Conservation Letters, 13(4), e12711.

World Bank. (2021). Climate-smart agriculture investment plan: Improving resilience and productivity. World Bank.

Zomer, R. J., Neufeldt, H., Xu, J., Ahrends, A., Bossio, D., Trabucco, A., … van Noordwijk, M. (2020). Global tree cover and agroforestry carbon potential. Scientific Reports, 10, 20776.

Zomer, R. J., Trabucco, A., Wang, M., Lang, R., Chen, H., Metzger, M. J., & He, J. (2022). Environmental stratification to monitor and model agroforestry systems. Remote Sensing, 14(3), 547.