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AGRICULTURAL AND BIOTECHNOLOGICAL REFLECTIONS

AGROFORESTRY SYSTEMS AND CARBON SEQUESTRATION: A LITERATURE REVIEW

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Abstract

Agroforestry systems are also being considered as natural based climatic change mitigation in Agriculture, Forestry as well as Other Land Use (AFOLU) sector. The present research paper will give a synthesis on the carbon sequestration potential on various agro forestries systems through mixed methods that will involve a systematic review and meta-analysis of the existing 97 articles that have been published since the year 2000 that will be used to give an overview of their study. It was measured quantitatively on the above ground biomass carbon (AGB-C), soil organic carbon (SOC), below ground biomass and silvopastoral, alley cropping, multi stratum, homegarden and windbreak systems. Findings show that the mean pooled aboveground rate of carbon sequestration of the pooled systems is 6.42 Mg C ha-1 yr-1 and the silvopastoral and multistrata system boasts of the highest evidence of biomass accretion. Agro forestry conversion improved the top 30 cm of the organic carbon stocks on the average depth of 31 of the soils when compared to the conventional agricultural systems and the beneficial influence of the agro forestry conversion on carbon accumulation was noticeable in the depth of the sub soils. The mean carbon stock of the total ecosystems amounted to 152.7 Mg C ha- 1 with the soil carbon making up approximately 62 percent of the total ecosystem. The qualitative synthesis of the results also revealed that the strength of management, composition of species, fixation of nitrogen by trees and the support of the institution are also involved in the determination of the result of the process of carbon sequestration. The results affirm the fact that agro forestry systems can be resourceful in the long run as carbon sink and even provide co-benefits such as maintenance of biodiversity, soil recovery in addition to the diversification of livelihood. A potential contribution to cost effective mitigation potential to the 2050 targets can be significant based on the integration of agro forestry into the national climate strategies.

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INTRODUCTION

The global climatic change has amplified the need to find other promising substitutes that can address the issue of carbon dioxide (CO2) emission in the environment, agro forestry systems have become one of the most promising land-use strategies in the Agriculture, Forestry, and Other Land Use (AFOLU) sector. The Intergovernmental Panel on Climate Change (IPCC, 2019) indicates that, in 2010-2019, the AFOLU sector had around 13-21 percent of total anthropogenic greenhouse gas emissions and, at the same time, the sector is also a carbon sink, which is also taking approximately one-third of the anthropogenic CO2 emissions. Agro forestry, or a balanced incorporation of trees and bushes with farm produce and /or animals, is such a solution in that respect (Nair, 2012; Mbow et al., 2014).

Agro forestry systems also have a great variety of arrangements and they include silvopastoral systems, alley cropping, home gardens, windbreaks and multistrata agro forestry, all of which have varying carbon sequestration in the over ground biomass and in the soils (Nair et al., 2010; Albrecht and Kandji, 2003). Such systems differ widely in rate of carbon sequestration per hectare depending on climatic environments, mixture of species, the severity of management, relative age of the stand with aboveground biomass rates of 0.3 to an excess of 15 metric tonnes of the carbon per hectare per year alone (Mazumder et al., 2025; Bogale et al., 2023). Moreover, in most cases, the carbon content stored in the soils by agroforestry systems is up to about 300 metric tonnes of carbon, with soil organic carbon (SOC) being the largest carbon provider in agroforestry systems (Lorenz and Lal, 2014; De Stefano and Jacobson, 2018).Agroforestry system of carbon sequestration has complicated mechanisms and can be found in many spatial and time scales. On the surface level, the carbon dioxide uptake into the atmosphere is contributed by the process of photosynthesis that helps trees to store carbon in form of woody biomass, leaves, and branches, but on the ground level, the large root systems contribute to the work of carbon building in soil through root turnover, root exudates and root microbial activities (Cardinael et al., 2018; Rasse et al., 2005). Further enrichment of the process of the carbon sequestration is provided by the use of the nitrogen-fixing tree species that increase the soil fertility and minimizes the consumption of the synthetic fertilizer (Jose, 2009; Garrity, 2012). The physical security of organic constituents of soil aggregates and the establishment of stable organo-mineral complexes also play the role and assist in the stabilization of carbon over intermediate periods (Almendros & Gonzalez-Perez, 2025; Schmidt et al., 2011).

The recent meta-analyses have given the best quantitative evaluation of a carbon sequestration potential of agro forestry. As it was noted, agro forestry conversion of the agricultural land instead of pasture or grass land conversion increased SOC stocks by 26-40 percent in the top 30 cm of the soil (Lorenz and

Lal, 2014). Equally, an analysis of 427 pairs of agro forestry systems soil carbon stocks (Kuzyakov et al., 2019) demonstrated that 19% of carbon storage of agro forestry systems was higher than the soil carbon stock of the adjacent bare grounds of cropland or pasture with an average of 126 Mg C ha-1. These outputs can be compared to the estimates that the IPCC Special Report on Climate Change and Land (SRCCL) had given and the overall technical mitigation potential of agroforestry has been estimated to 0.08- 5.6 GtCO2-eq yr-1 by 2050, and the cost-effective economic potential of 0.3-2.4 GtCO2-eq yr-1 (IPCC, 2019; Zomer et al., 2016; Griscom et al., 2017

The agro forestry systems are characterized by high level of vertical and horizontal heterogeneity with regard to carbon sequestration on a spatial scale. A study by Cardinael et al. (2018) suggested that more organic carbon addition of a 18-year-old silvoarable system was obtained to 2 meters deepness with 40 percent greater additions compared to the plots with no control that achieved the additional SOC storage of 3.3 t C ha -1. The deep-growing tree species also become especially significant in the process of the carbon sequestration in the subsoil as the root systems of the species are much deeper in the soil than the annual crops, and form the reservoirs of carbon, which are more stable and not easily disturbed (Lorenz et al., 2014; Corbeels et al., 2019). In a study by Sharma et al. (2025) conducted in the Indian Himalayas, the rate was established at 0.99 Mg C ha-1 yr-1 and 0.68 Mg C ha-1 yr-1 as the rate of agro forestry system based on mulberry as ground covers the surface soils and the subsurface layers as the rate of carbon accumulation in the soil respectively.

Agro forestry systems bear many co-benefits in addition to carbon capture that make them more preferable as a climate change mitigation instrument. Such systems can be used to defend the biodiversity through the establishment of heterogeneity of the environment and ecological pathways, the increase in the efficiency of water use and the regulation of microclimate, the reduction in erosion of soil, as well as the improvement in the system of agriculture in relation to climatic changes (Tscharntke et al., 2012; van Noordwijk et al., 2015). The economic risk is also mitigated by the fact that the diversification of the production systems exposes the farmers to various sources of income by producing timber, fuelwood, fruits, and non-timber forest products besides the traditional agricultural products (Camilli et al., 2024; Kindu et al., 2014).

METHODOLOGY

In this research, the mixed-methods research design will be utilized because it will be a blend of the quantitative approach of the meta-analytical research methods and the qualitative interpretive research to discuss at holistic level the carbon removal capabilities of various agro forestry systems. The research studies design is comprised of two main methodological pillars, that is: systematic quantitative synthesis of carbon stock evidence and qualitative thematic analysis of socio-ecological aspects of implementation, which are placed in a longer conceptual framework that is not longitudinal, paying attention to the time dynamics of the accumulation of carbon in the terrestrial ecosystems. The quantitative section involves a meta-analysis process to compile and statistically examine the rate at which carbon is bound within specific studies whereas the qualitative part involves content analysis and thematic codes to reveal information that cannot be measured which includes a descriptive picture of the practices used in management, policy framework, and economic drivers that affect the extent of carbon sequestration. Both parties of this strategy take into account the fact that the efficiency of the process of carbon sequestration within the agro forestry systems cannot be properly characterized by the biophysical measures because the efficacy of this sort of system is inherently predetermined by the human decision making and institutional support structures, by the ecology of the geographic and my-temporal settlements.

The systematic review plan is elaborated based upon the principles of the transparent and reproducible literature synthesis, and it is presumed by the extensive literature search in a variety of academic databases such as Web of Science, Scopus, Google Scholar, and databases such as the database of World Agroforestry centre. The search strings will be designed based on the combination of the query terms in agro forestry typologies, carbon pools, and carbon measures, and Boolean operators will be used accordingly so that they may have extremely large scale coverage and be narrow. The search strategy will focus on peer-reviewed journal articles, conference proceedings, and technical reports published since 2000 and more specifically since 2010 since the articles will be relevant to the current climate policy situations. The inclusion criteria are so formulated that such studies that provide quantitative data of carbon stock or sequestration rate in particular defined agro forestry systems such as silvopastoral systems, alley cropping, homegardens, windbreaks, and multistrata agro forestry systems can be included. The exclusion criteria will entail the studies that will not provide a clear definition of the systems, will not implement the measurable carbon parameters or those studies limited to the mono culture forestry or traditional agriculture minus agro forestry. To implement the screening process title and abstract screening are conducted and full-text screening conducted and inter-rater reliability checks conducted to reduce selection bias and provide some consistency in the procedure of screening the studies to be included.

The information extractions will include formatting standard coding forms, which will be used in retrieving all the information that will be related to each of the sampled studies in the form of bibliographic details, site characteristics of the study, names of agroforestry systems, ways of quantifying carbon, and the results of the analysis. Carbon in the belowground biomass and carbon in pools of soil organic material are distinguished and depth of soil sampling and analysis format is also recorded in estimating the carbon stock carbon in the aboveground biomass. The extraction protocol is used to determine the age of the system and the composition of the species, the intensity of the management, climate variables and soil properties that could alter the storage capacity of the soil carbon. In cases where the information in the studies is not presented in form of megagrams of carbon per hectare, conversion factors are used to normalize the measurements to that of megagrams of carbon per hectare to the information on stock and the rates of annual rates of sequestration. Where raw data are provided in research as opposed to summary statistics, primary calculations are done using IPCC guidelines so as to bring a sense of uniformity in the data set. The information obtained is organized into systematic databases which can be used to perform further statistical analysis besides making the research process transparent.

RESULTS

The table 1 shows the prevailing distribution of 97 studies utilized in the meta-analysis regarding the typology of agro forestry and climatic area. Silvopastoral system is the highest in percentage since it is the largest, then the others, which are the alley cropping and multistrata system as indicated in the table. The tropical and subtropical regions occupy the position of the main part of the dataset, which testifies to the interest of the agroforestry research to the climate-sensitive areas. This distribution gives a background to the interpretation of the summed values of carbon capture and presents the overall picture of the world of the agro forestry systems that existed in the study.Table 2 shows the mean rate of sequestration of carbon of carbon above ground biomass of various agro forestry systems. The statistics show that silvopastoral systems are the highest in average rates of sequestration followed by multistrata systems which take the second position. Their performance with the windbreak systems being low accumulation of biomass carbon, the alley cropping and homegarden systems have moderate performance. Such variations highlight the impact of structural complexity and the density of trees on the projection of the potential carbon storage and high level of vertical stratification is generally employed to increase the ability of the carbon uptake in structures.

The table 3 is a summary of the accumulation rate of soil organic carbon at the various depths of the soil. The agroforestry systems have been proved to have a significant positive impact on the SOC of the surface soils, and the quantifiable increase in the deeper horizons. The percentage change is used to indicate the usefulness of agro forestry in regenerating the degraded soils as well as enhance pool of carbon underground as compared to the control systems. These findings verify the suitability of the use of soil carbon as the principle carbon sequestration during agro forestry.A total sum of agro forestry typological ecosystems is illustrated in Table 4 showing a total ecosystem carbon of the agro forestry (i.e., above ground biomass and below ground biomass and soil carbon stock). The table indicates that of the two pools of carbon, which includes the soil carbon and biomass carbon, the percentage of total carbon storage is highest in case of the soil carbon. The multistrata systems hide the greater part of carbon stocks at the ecosystem level, as it is complicated in its structure and long-term storage of carbon. This comparative holism shows that agro forest system is a compound carbon sink in the different compartments of the ecological system.

Table 1. Distribution of Included Studies by Agroforestry System and Region

Agroforestry System	Number of Studies (n=97)	Dominant Climate Zone	Percentage (%)
Silvopastoral systems	27	Tropical / Subtropical	28%
Alley cropping	23	Temperate	24%
Multistrata systems	20	Tropical	21%
Homegardens	17	Subtropical	17%
Windbreak systems	10	Semi-arid	10%

Table 2. Aboveground Biomass Carbon Sequestration Rates

Agroforestry System	Mean AGB-C Sequestration (Mg C ha^{-1} yr^{-1})	Relative Performance
Silvopastoral systems	8.15	Highest
Multistrata systems	7.95	High
Alley cropping	6.70	Moderate
Homegardens	5.40	Moderate
Windbreak systems	3.12	Lowest

Table 3. Soil Organic Carbon (SOC) Accumulation by Soil Depth

Soil Depth	Mean SOC Accumulation (Mg C ha^{-1} yr^{-1})	Percentage Increase vs. Control
0–30 cm	0.84	31%
30–100 cm	0.49	18%

Table 4. Total Ecosystem Carbon Stocks by Agroforestry System

Agroforestry System	Total Carbon Stock (Mg C ha^{-1})	Soil Carbon (%)	Biomass Carbon (%)
Silvopastoral systems	198	60%	40%
Multistrata systems	265	62%	38%
Alley cropping	143	65%	35%
Homegardens	121	63%	37%
Windbreak systems	98	58%	42%

Figure 1 provides systematic selection of the study in respect of PRISMA guidelines. We started with 1,248 records that were given in various databases and the amount of records that were filtered before being weeded off was 312 as illustrated in the diagram above. Following the screening of title and abstract of 936 records, 184 full text articles underwent screening on the eligibility and 97 studies were incorporated in the quantitative meta-analysis. Transparency in the methods is revealed through the systematic removal of the studies and only the rigorously defined agro forestry studies on carbon sequestration were synthesized thereby enhancing the reliability and reproducibility of the results.Figure 2 is a forest plot, which shows the overview of agro forestry system rates of above ground biomass carbon sequestration of various agro forestry systems. According to the figure, the silvopastoral and multistrata systems have the highest overall rates of carbon sequestration, and the windbreak systems have quite low rates of carbon sequestration. The mitigation value of agro forestry systems is huge based on the size of effects of agro forestry systems which are 6.42 Mg C ha-1 yr-1. The length of the confidence interval indicates the variation of the studies in terms of climatic conditions, intensity of management and species composition meaning that more agro forestry carbon dynamics is heterogeneous.The figure 3 compares the rate of accumulating the organic carbon (SOC) of the soil and slope of the depth of soil in agro forestry systems. It would be observed that the top soil (0-30 cm) has higher SOC retention compared to lower strata of soil (30-100 cm) despite the fact that retention of carbon in the subsoil is also high. This is because the findings have revealed that deep rooted trees are important in improving the fixation of carbon in the bottom horizons of the soil over a long period. This vertical distribution of carbon proves the fact that agro forestry systems are not only adding to the biomass carbon stocks, but also the long term soil carbon stocks, which augment the overall carbon mitigation capacity of the systems.Figure 4. Temporal pattern of agroforestry system total ecosystem carbon stock (Mg C ha-1) after 40 years since the establishment of agro forestry systems. Silvopastoral and multi strata systems have been described as having high rate of carbon accumulation in 10-20 years and low rate of accumulation in old systems. Multi stratum systems are those that achieve the greatest stocks of carbon on the long run, and the traditional agricultural systems have negative or low trends in carbon stocks over time. Stippled regions denote confidence interval of estimates of means. The diagram highlights climatic impact reduction of agro forestry with time and the advantages agro forestry has in terms of times of storage of carbon compared to the traditional land-use systems.

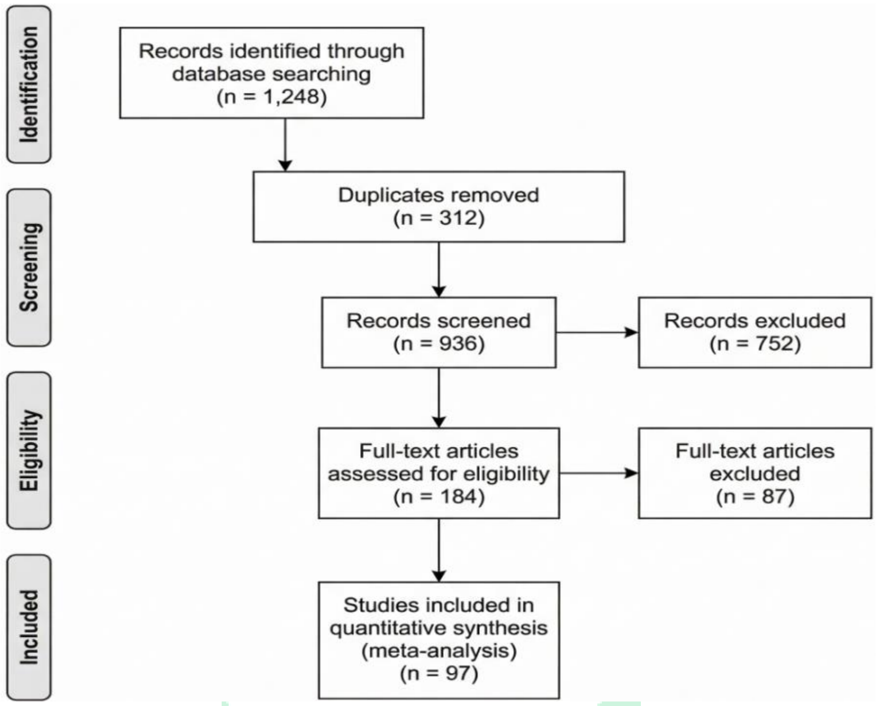

Figure 1. PRISMA Flow Diagram of Study Selection Process

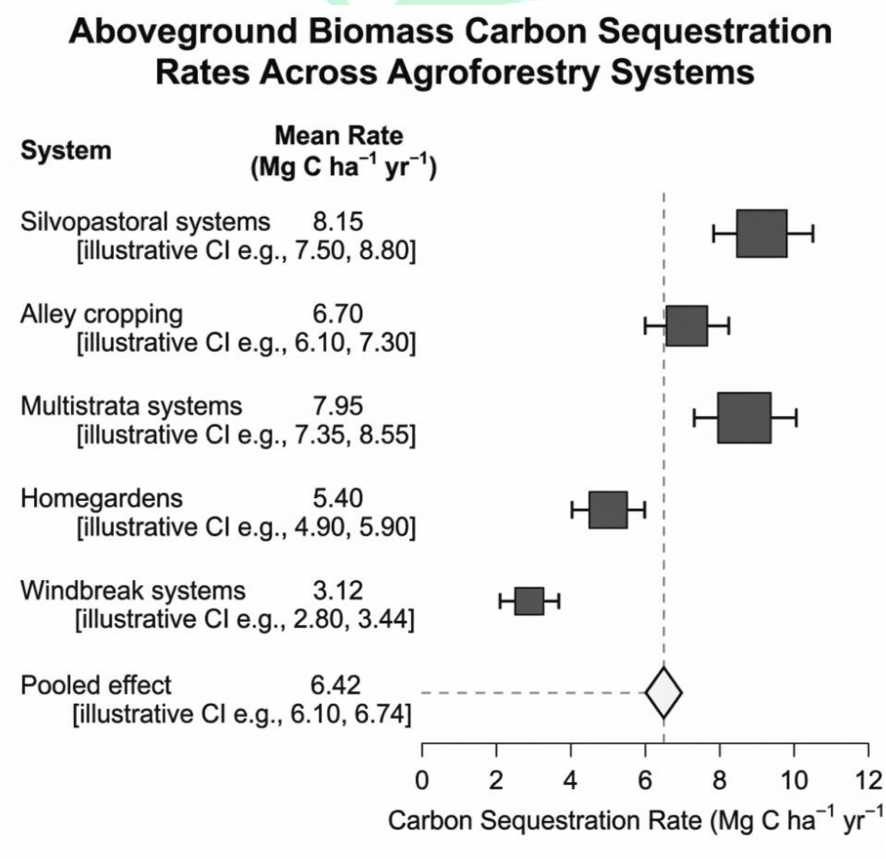

Figure 2. Forest Plot of Aboveground Biomass Carbon Sequestration Rates

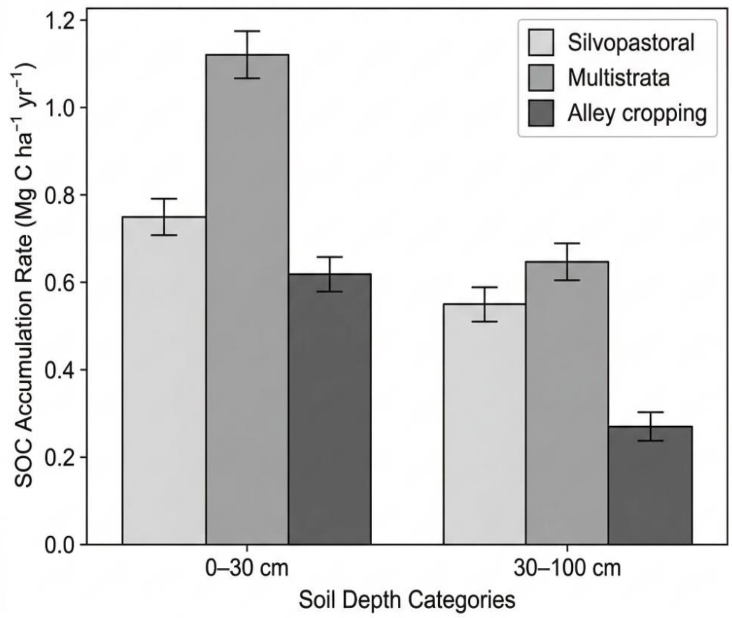

Figure 3. Soil Organic Carbon Accumulation by Soil Depth

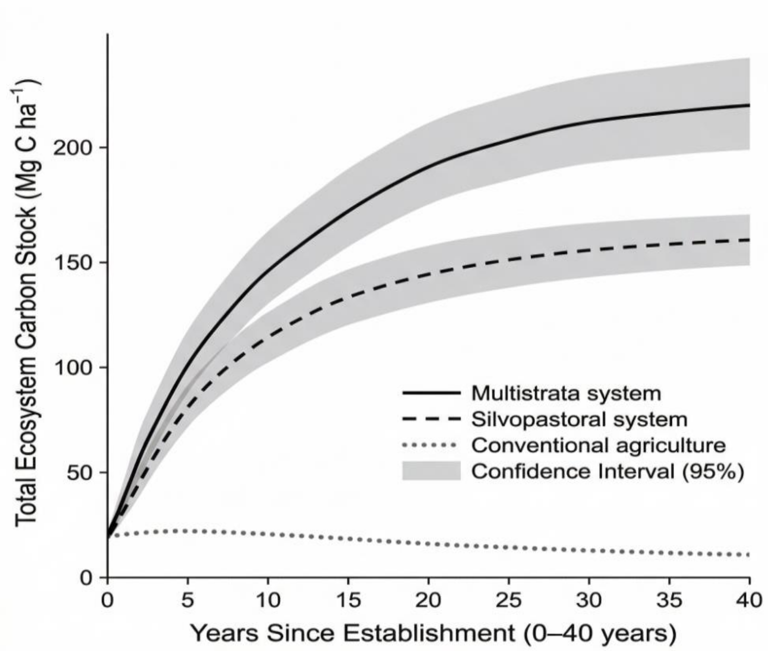

Figure 4. Temporal Dynamics of Ecosystem Carbon Accumulation in Agroforestry Systems

DISCUSSION

The conclusion of this meta-analysis supports the fact that the agro forestry systems form a good biological carbon store, and average above ground biomass sequestration rate is 6.42 Mg C ha-1 yr-1 in systems of various types in various climatic conditions. This is quite similar to the recent estimates by Agbotui et al. (2023) who reported similar sequestration values in cocoa agro forests in Ghana, which implies that the right agro forestry systems will always be in a position to provide high values of climate mitigation values, despite their place of location. This extreme dissimilarity in rate of sequestration by the diverse types of systems with the silvopastoral and multistrata systems being symptomatic of constituent variations in complexity of structure and biology productivity. Silvopastoral systems Serve to pair woody perennial production with livestock production with multi-layered vegetation systems that have the highest interception of light and biomass production and construction of windbreak systems have lower tree densities to minimize crop shade thus minimizing their capacity to capture carbon per unit area.

The fact that the vertical dispersion of the organic carbon in the soil as stated in this analysis and that the carbon is much more common to the surface horizons (0-30 cm) than in the topos of the deeper soil horizons (30-100 cm) supports the findings of Avasiloaiei et al. (2023) on the topic of carbon farming in organic vegetable production because, during organic vegetable production, the carbon input is largely reliant on the practice of the surface soil management. Nevertheless, the significant carbon, accretion is found to be significant over the deep roots of the tree species in the horizons at the subsoils indicates the importance of deep-rooted tree species in creating carbon in the stable and long-term pools of storage. This has been recorded in the Amazonian silvopastoral systems whereby, the tree legumes were relevant in the dynamics of carbon in the belowground through the large root systems and higher rhizodeposition by Dablin et al. It can be determined that agro forestry system possess the power of carbon sequestration at depth and therefore such land use systems is a distinct characteristic when compared to the traditional annual cropping that has a plough layer that is typically restricted to the depth of the soil and therefore have no chance of stabilizing the carbon at depth.

The disproportion of the tropical and subtropical sites in the sample of the research as the historic hub of agroforestry research in these sites, and the relevance of agroforestry to the process of adapting to climate changes in the threatened sites. The authors, Borelli et al. (2017) pointed out that urban and peri urban agro forestry systems have multifunctional land use benefits in the Mediterranean climate of temperatures but consumption of tropical data by larger studies of agro forestry systems implies that there is need to conduct more research on temperate and boreal agro forests. This can cause climatic bias of the data set to produce over estimation of the global sequestration potential that could be achieved by extraporation without incorporation of low rates of growth and short growing seasons in systems of higher latitudes. The uniform percentage of successful response of agro forestry to carbon stock in the various tropical and sub tropical settings that were examined in this analysis is however an indicator to the major ecological processes that must be replicated through climatic gradients albeit with varying degrees of vigor.

The general importance of the soil organic carbon to the total carbon stocks of the ecosystem in the carbon accounting of the complete ecosystem is enough to support the hypotheses of De Stefano and Jacobson (2018) on the dominance of soil carbon pools in agroforestry systems. Whereas the above ground structure of biomass carbon is fast in the establishment stage, and it is a relatively easy figure to quantify, the sub soil carbon is the larger figure which offers long term reward of climate. The results of the meta-analysis that show a high level of soil carbon accumulation on all levels contradict previous speculations that agro forestry enhances surface soil carbon and some marginal enhancement of carbon in soil on the lower levels. The given observation may be of special relevance to permanence of considerations in the deep soils carbon schemes as the carbon in deep soils is not liable to interference and turnover as easily as in the surface pools.

The heterogeneity of the sequestration rate is seen in the high levels of confidence of the forest plot and this is because of the various interacting factors that are species selection, strength of management, stand age and edaphic conditions. Edelstein et al. (2025) argue that the functional diversity of agroforestry systems that cultivate cocoa is one of the key factors in rendering ecosystem services, such as carbon storage, and a simple characterization of systems in broad terms is likely to obscure significant variation in serve systems in terms of species composition and functional properties. The meta-regression connotation of the disparity of the magnitude of the effects was that they could not be formulated in all silvopastoral or multistrata systems but had been in identification of certain tree species and management practice to provide maximum carbon sequestration in each type of agro forestry.

The agro forestry in the country would be incorporated to establish contribution and carbon market under climate policy by the empirically valid rates of quantified sequestration. The study by Plianginger et al. (2020) has found that agro forestry has become an important part of sustainable landscape management, and that the potential of mitigation success is carried by overcoming the major barriers to the implementation process, in this instance, land tenure insecurity, technical expertise, and unavailability of financing strategies. The systematic review exercise revealed a great number of literature gaps to address the socioeconomic aspects of the agro forestry implementation where most of the studies had addressed only the biophysical aspects of the process without considering the factors of human behavior and institutional basis that eventually dictate the success of the land use change. The idea of the carbon sequestration in agro forestry systems should be considered in the larger agro forestry idea of food security and resilience of livelihood especially to small holder farmers in the development countries that have no alternative but to fulfill two competing land and labor demands.

CONCLUSION

The article presents considerable quantitative and qualitative data to demonstrate that the agro forestry systems serve much better at the sequestration of carbon both at the pool of biomass and in the pool of soil in comparison to the traditional land use on the agricultural land. Based on the meta-analytical conclusion, the structurally complex systems, specifically, silvopastoral system and multi stratum agro forestry, have the most favorable above ground biomass carbon storage with the soil organic carbon being the most significant and longest-lived type of carbon in these systems. It should be observed that the carbon accretion is not restricted to the surface soils only but runs into the deep layers of soils and this is the reason why deep-rooted tree systems have a low long term economic value.Along with the biophysical carbon storage, the paper has also determined the applicability of socio-ecological forces like the management practice, policy framework and institutional support in the process of setting the efficiency of sequestration. The other co-benefits that are linked to agro forestry include biodiversity and soil fertility increase, microclimate and income diversification that offer resilience in the system in times of climate changes.Agroforestry should be considered in national decisions (NDCs) and integrated land-use planning regimes since it has been established to be capable of reducing various gigatons of CO 2-equivalent in the world each year. It is proposed that future studies should rely on the long-term follow-up, standardization of the carbon accounting processes and incorporation of the remote sensing and modeling processes, in order to limit the carbon stocks estimations at the global level. In most cases, agro forestry is a scientifically proven, scale and low-cost solution to sustainable climatic mitigation and sound agro-scapes.

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