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Carbon sequestration potential of agroforestry systems in Indian agricultural landscape: A Meta-Analysis

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ABSTRACT

Agroforestry (AF) systems offer numerous ecosystem services and environmental benefits to humanity. Compared to conventional agricultural practices, these systems have the potential to address the impacts of climate change through carbon (C) sequestration. We examined the impacts of four dominant AF systems, viz., agrisilviculture, silvipasture, agrihortisilviculture, and agrihorticulture, on soil C sequestration and the influencing factors as well as associated benefits. Results revealed that conversion to agroforestry systems resulted in a considerably higher C sequestration (+25.34%) compared to non-agroforestry systems. The highest mean soil C stock was found in agrihorticulture (38.11 Mg C ha^{-1}), which is + 31.64% higher in comparison with conventional systems. The transformation from grasslands to agroforestry systems resulted in the highest carbon sequestration, with an increase of + 36.94%. In contrast, the transition from forest to agroforestry systems resulted in a decline in soil C sequestration (–23.42%), implying its sequestration potential outside the forest rather than the substitute of forests. AF in semi-arid subtropical regions showed higher sequestration potential compared to other regions. Further, higher C sequestration was observed in younger trees (+39.51%) and in the upper soil layers (upto30cm) of AF systems. Factors such as previous land use, system type, age, and rainfall were the major drivers of soil C sequestration in AF systems. Our findings also indicated that all the AF systems considered are technically feasible and economically profitable in the Indian agricultural landscape. Reorienting and extending incentives for agroforestry, improving certification standards for agroforestry products, and strengthening the AF extension system will be crucial in enhancing ecosystem services and supporting India's efforts toward achieving its net zero emission target.

1. Introduction

Agricultural intensification and cropland expansion, although pivotal for fulfilling the food and nutritional demand of an ever-growing population, are also considered major drivers of environmental degradation and disruption of the ecosystems globally (Campbell, et al., 2017; Power, 2010; Zabel et al., 2019; Wassie et al., 2020). Implementing intensive agricultural practices results in the degradation of natural resources, biodiversity loss, and greenhouse gas emissions, which severely threaten agricultural sustainability (Roul et al., 2020). Additionally, the negative impacts of climate change lead to further deterioration of several ecosystem services and increase the vulnerability of small and marginal holders (Peng et al., 2020). Therefore, promoting and adopting climate-smart conservation practices is necessary to mitigate climate change impacts and conserve natural resources (Kumara et al., 2020). According to the United Nations Department of Economic and Social Affairs (UNDESA, 2022), India is projected to become the world's most populous country by 2023. This will further fuel the already declining per capita availability of agricultural land in the country. The adoption of intensive farming practices to meet the country's food and nutritional requirement severely threatens natural resources and ecosystem services. Cultivation of degraded land, deforestation, and indiscriminate use of external chemical inputs lead to soil carbon depletion and other vital nutrients. (Blanco-Canqui, 2017; Feng et al., 2018). Conversely, sustainable land management practices (SLM) have the capacity to capture and store atmospheric carbon without affecting the supply of other ecosystem services (Bommarco et al., 2013; Feliciano et al., 2013).

Changes in land use dynamics significantly influence soil carbon stock and affect the carbon-carrying capacity of the land (Bolin and Sukumar, 2000). The human-induced land use changes have the ability

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to reduce CO_2 emission in the atmosphere through an increase in organic carbon content in the soil (Hutchinson et al., 2007; Guo and Gifford 2002). Feliciano et al., (2018) emphasized that Agroforestry (AF) has the ability to decrease greenhouse gas (GHG) emissions through C sequestration, particularly in tropical regions. Therefore, higher C sequestration is possible in the agricultural landscape through crop diversification together with the implementation of SLM practices (Tamburini et al., 2020). As a result, tree-based-land use systems, including agroforestry, were incorporated as GHG offset activity during the Kyoto Protocol in 2001(Nair et al., 2009). However, it is suggested that efforts to mitigate climate change impact through augmenting soil organic carbon must be coupled with addressing other socio-economic challenges simultaneously (Batjes, 2004).

Agroforestry (AF) systems have been identified as ecologically based food production systems compared to conventional farming and forestry practices and offer numerous socio-economic and environmental benefits (Torralba et al., 2016). Food and Agricultural Organization (FAO) defines AF as *"the spatial arrangement or temporal sequence of land-use systems and technologies where woody perennials are deliberately integrated on the same land-management units as agricultural crops and/or animals."*." In contrast, India's National Agroforestry Policy defined the agroforestry system as the "*integration of trees and shrubs along with the cropping systems to enhance system productivity, economic profitability, biodiversity, and ecosystem sustainability.*" AF systems effectively utilize the land and act as a stimulant to the supply of ecosystem services, playing a critical role in the rehabilitation of degraded wastelands (Röhrig et al., 2020). Many studies highlighted key benefits of agroforestry systems, including additional income (Foster and Neufeldt, 2014) and climate regulation services, primarily C-sequestration (Millennium Ecosystem Assessment, 2005). AF also provides high socio-cultural benefits, biodiversity conservation, raw materials, prevention of soil erosion, and nutrient losses (Oteros-Rozas et al., 2018; Crous-Duran et al., 2020). However, the supply of ecosystem services from agroforestry systems primarily depends on cropping intensity and changes in land cover (Rolo et al., 2021). Furthermore, agroforestry is also recognized as one of the sustainable farm management practices to address global climate change impacts (IPCC, 2019).

In India, AF is an age-old traditional resource management and adaptation practice where trees and pastures are intentionally incorporated into the existing cropping systems. Conventionally, AF systems are primarily adopted due to symbiotic relationships between crops, trees, and livestock in addition to food and fiber (Chavan et al., 2015). Most of the AF systems are established by local knowledge of rural communities; therefore, AF systems vary according to the region and prevailing climatic conditions (Chavan et al., 2015).

Currently, AF systems are adopted in an area of 25.32 Mha in the Indian agricultural landscape, which is equivalent to 8.2 percent of the total geographical area (Dhyani et al., 2014). Agroforestry substantially contributes to the Indian economy by improving the livelihoods of millions of households. According to Handa et al., (2016), AF can generate employment opportunities for up to 943 million person-days per year in the country. Further, as a climate change target, in 2014, India implemented National Agroforestry Policy to address the research, extension, production, and marketing issues related to AF-based products. Thus, the wider adoption of AF has the potential to enhance the diversity in ecosystem services through interactions and optimum utilization of land at various scale-from field to farm, and the overall agricultural landscape of India.

In the past two decades, a plethora of studies estimated the carbon sequestration potential of AF systems by comparing it to conventional practices. For example, Panwar et al., (2022) *meta*-analysis study highlights the variation in biomass and soil organic stocks among agroforestry systems. The study also indicates that the biophysical growth and characteristics of agroforestry tree species are critical for the carbon storage capacity of AF systems. However, the study does not consider the dynamics of land use change and other environmental factors on C sequestration and the economic feasibility of AF systems for carbon sequestration. Further, most studies lack the proper control plots for comparison, resulting in inaccurate estimation. As a result, the estimates are highly divergent. Thereby it is challenging to draw an extent C sequestration from AF systems. In addition, C sequestration is driven by geographical regions, climatic and soil conditions, age of the system, rainfall, and other agronomic factors (Bai et al., 2019; Kumara et al., 2020). This study aims to synthesize the findings of various peer-reviewed studies on C sequestration potential in AF systems in the Indian agricultural landscape using a *meta*-analysis framework. The specific objective of this study is (i) to quantify the soil C sequestration potential in four AF systems, viz., Agrisilviculture, Agrihorticulture, Agrihortisilviculture, and Silvipasture; (ii) to evaluate the impacts of land use change, soil depth, age, and climate conditions on the performance of AF systems; (iii) to comprehend the drivers of C sequestration in AF systems; and (iv) economic feasibility of AF systems for C sequestration.

2. Materials and methods

2.1. Data collection

We conducted a comprehensive search for peer-reviewed research studies comprising different AF systems until June 2021. The keywords used to identify the peer-reviewed research articles are 'agroforestry', 'agrisilviculture', 'agrihorticulture', 'agrihortisilviculture', 'silvipasture', 'alley cropping' along with 'soil organic matter', 'soil organic carbon', 'carbon' and 'carbon sequestration.

The studies were selected based on the Shi et al., (2018), and Feliciano et al.,(2018) criteria: (i) The information on soil organic carbon had to be reported along with the comparison of AF systems vis-à-vis non-agroforestry land use, (ii) The study had to provide information on land use before the adoption of the AF system, and (iii)The detailed information of the experiment conducted such as location, age of the system, soil depth, and climate was specified. In cases where the information on soil carbon was not directly reported in the study, it was estimated indirectly using bulk density and soil depth data. AF systems were classified as < 10, 10–20, 20–50, and > 50 years old based on their establishment age. They were further categorized based on soil depth as 0–15 cm, 15–30 cm, 30–50 cm, and 50–100 cm soil depth systems. The climates were classified based on Köppen's climate system into four groups: humid subtropical, semi-arid, semi-arid subtropical, and wet-temperate. The list of publications used in this study is available as supplementary material, provided separately. The selected studies were distributed across 16 states, covering four major AF systems in the country (Fig. 2).

2.2. Database

Table 1 represents a summary of the data included in the *meta*-analysis. After eliminating outliers, 423 observations from 46 studies were incorporated into the final analysis. The number of observations under each AF system is Agrisilviculture (54.85%), Silvipasture (26%), (13.29%), Agrihortisilviculture (12.06%), and Agrihorticulture had 7.09 percent observations (Table 2). Further, the dataset had five land use systems representing agriculture, forest, pasture, uncultivated, and grassland. The overall mean age of establishment of different AF systems ranges from 15.25 to 17.19 years.

2.3. Statistical tools

2.3.1. Meta-analysis

Meta-analysis has become a popular statistical tool in recent years due to its flexible approach over other techniques. It is the most powerful statistical technique used to combine the findings of various studies conducted under diverse agro-climatic environments (Hedges

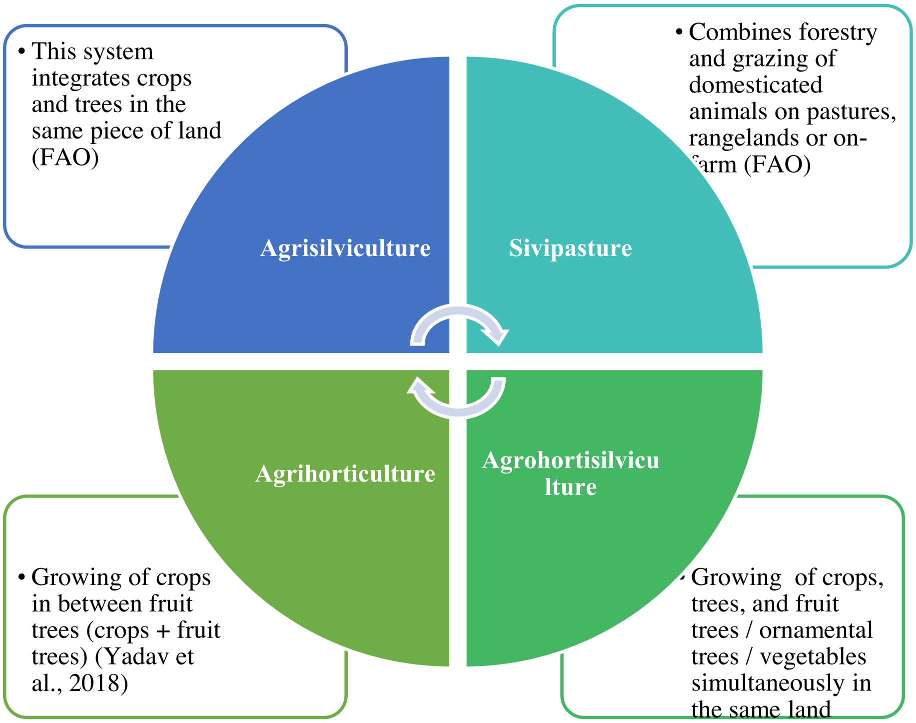


Fig. 1. Classification of AF systems in the Indian subcontinent.

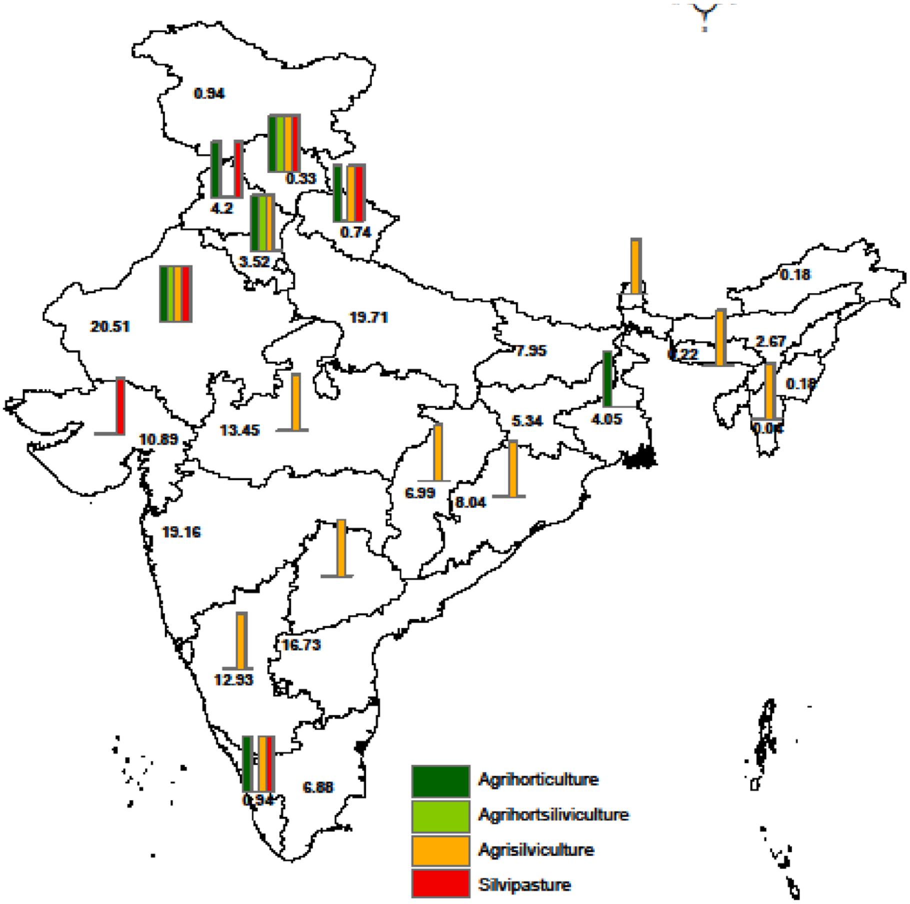


Fig. 2. Distribution of study locations(The values inside the map indicate state-wise area under agroforestry (in Mha)).

Table 1
Summary of data used in the *meta*-analysis.

Category	Observations	Studies	Age of the system (Years)[a]
All	423	46	15.99 ± 13.19
Agrisilviculture	232	28	15.25 ± 11.56
Agrihorticulture	30	8	15.35 ± 5.56
Agrihortisilviculture	51	4	17.19 ± 14.86
Silvipasture	110	11	15.99 ± 13.39

[a] Mean ± Standard Deviation.

et al., 1999). Numerous research studies in the area of natural resource economics have employed a *meta*-analysis framework as a method, including those by Cadotte et al. (2012), Kumara et al., (2020), and Nelson and Kennedy (2009).

To evaluate the relative difference in soil C sequestration, we treated AF systems, and agriculture/pasture/grassland/forest as treatment and control groups respectively. The Response ratio (RR), the ratio of the treatment group outcome variable to that of the control group, was used to calculate the effect size of each study (Hedges et al., 1999).

$$\text{Effect size} = \ln \text{RR} = \ln\left[\frac{\overline{X}_T}{\overline{X}_C}\right] = \ln\overline{X}_T - \ln\overline{X}_C \tag{1}$$

Where $\overline{X}_T$ and $\overline{X}_C$ are the mean soil organic carbon stocks (Mg/ha) of treatment and control groups, respectively. As some of the studies were not reported the standard deviation and variance of means, we imputed the missing standard deviation using the coefficient of variation (Bracken, 1992; Wiebe et al., 2006). Finally, the LRR was calculated and back transformed into a percent change which was computed as

$$Percent\ change = \ (exp\ (LRR) - 1\,)*100 \tag{2}$$

The analysis was performed in R software with a metaphor package (Viechtbauer, 2010), and forest plots were constructed using ggplot2 (Wickham, 2017). The heterogeneity among the studies due to random variation was captured using the random effect models (Borenstein et al., 2009). The potential publication bias was also evaluated by using funnel plots and Egger's test (See the supplementary information for details).

2.3.2. Generalized linear mixed (GLM) regression model

A Generalized Linear mixed (GLM) model was fitted to determine the factors of carbon sequestration potential in AF systems (Toliver et al., 2012; Kumara et al., 2019; Kumara et al., 2023; Feliciano et al., 2018).

$$\text{Carbon sequestration} = \alpha + \sum_{i=1}^{n}\beta_i F + \gamma_{sp} + \in \tag{3}$$

Where α is the intercept; β_i is the coefficient fixed effect; γ_{sp} represents the random intercept; and ∈ is the error term (Feliciano et al., 2018). States were added as a random intercept to address regional variability in the independent variables. The regression model was determined as follows:

$$\begin{aligned} lnRR =& \alpha_0 + \sum \alpha_i AFsystems + \sum \alpha_j Climate + \sum \alpha_k Control \\ &+ \alpha_l Age\ of\ the\ system + \alpha_{18} lnRainfall + (1|state) \end{aligned} \tag{4}$$

A step-wise modelling approach was followed, including different combinations of covariates. The best model was selected based on the highest R^2 and lowest Akaike information criteria (AIC). Significance was estimated using the Wald statistic. Further, the variance of data explained by random and fixed effects was estimated to quantify the impact of variables. Both marginal and conditional R^2GLM values were estimated (Nakagawa et al., 2013). All equations were estimated using the *'lme4'*, *'car,'* and *'MuMIn'* packages in R software (R Core Team, 2017).

Table 2
State-wise C sequestration potential of agroforestry systems in India.

Agro-climatic zone	States	AF system	Area[a] (ha)	Relative Change in C stock (Mg ha^{-1} yr^{-1})	Potential C sequestration (Mg CO$_2$e yr^{-1})
Western Himalayas	Himachal Pradesh	SP	228,490	0.25	208,160
Western Himalayas	Uttarakhand	AH	265,110	0.17	162,490
Eastern Himalayas	Arunachal Pradesh Assam Manipur Meghalaya Mizoram Nagaland Tripura West Bengal Sikkim	AS	68,740	0.1	25,730
Indo-Gangetic plains	West Bengal Bihar Uttar Pradesh Haryana Punjab	AS	671,500	0.76	1,872,940
Indo-Gangetic plains	Uttar Pradesh	AH	372,980	0.15	205,330
Eastern plateau & hills	Delhi Bihar	AS	185,770	2.21	1,506,740
Central plateau & hills	Rajasthan Uttar Pradesh	AH	133,430	0.22	107,730
Southern plateau & hill	Andhra Pradesh Karnataka	AS	579,910	1.18	2,511,360
East coast plains & hills	Andhra Pradesh Tamil Nadu Pondicherry	AS	61,100	1.1	246,670
West coast plains &hills	Kerala Maharashtra	AS	44,630	0.25	40,950
West coast plains &hills	Goa Karnataka	AS	66,940	1.34	329,220
Western dry region	Rajasthan	AS	193,770	0.09	64,000
	TOTAL		**2,872,370**		**7,281,320**

[a] Dhyani and Handa, 2014; Note: SP = Silvipasture, AH = Agrihorticulture, AS = Agrisilviculture.

2.3.3. *Economic assessment*

The economic assessment of carbon sequestration is a growing area of research and gaining a lot of attention globally in the recent past. The economic valuation of C sequestration comprises estimating the value of carbon sequestered and the costs required for maintaining and stabilizing carbon storage. By conducting an economic valuation, it is possible to determine the potential of agroforestry systems as an income-generating activity for the farmers through carbon credits and their economic viability in reducing emissions. However, there is a lack of credible methodologies for the valuation of carbon sequestration potential in AF systems. In the absence of a domestic carbon credit market in India, the social cost of carbon was used as a proxy, which represents the potential economic loss caused by the emission of one metric tonne of carbon. Thus, the social cost is used as a shadow price carbon of $86 per Mg CO_2e used for the valuation of carbon in AF systems (Ricke et al., 2018; Kumara et al., 2023). Further, the cost of stabilization of carbon storage was also incorporated in our analysis using urea (46 %N) at US$ 87.29 Mg^{-1} and soil C: N ratio of 14:1 of arable lands.

The economic benefits of C sequestration from AF systems were assessed using the approach followed by Lam et al. (2013), and Kumara et al., (2023):

(i) Value of SOC stock (US$/ha/year) = CO_2e (Mg/ha/ year)* Social cost of CO_2 ($/Mg of Co_2e)
(ii) Economic gain (US$/ha/year) = Value of SOC stock (US$/ha/year) –Stabilization cost (US$/ha/year)

In addition, to comprehend the discrepancy in the carbon market prices, we also performed the analysis using an actual carbon price of voluntary markets of 2021($8.81 Mg^{-1} CO_2) and the price essential to achieve the Paris temperature goal of limiting global warming to 1.5 °C (Donofrio et al., 2022). (See Supplementary Table S2).

3. Results

3.1. *Trends from the systematic review*

The results showed that the overall response of soil organic carbon to AF systems was primarily positive (82%). In contrast, only 18% had negative effects (Fig. 3). Out of the four AF systems, agrisilviculture and slivipasture showed the highest share of positive effect sizes in comparison with the other systems. Despite many research studies being conducted to assess the carbon sequestration potential across AF systems, agrisilviculture is the most frequently examined practice. However, agrihorticulture and agrihortisilviculture were less studied, which calls for further in-depth studies in these agroforestry systems.

3.2. *Soil C sequestration under major agroforestry systems*

Among the different AF systems, agrihorticulture had the highest mean soil C stock (25.61 Mg C ha^{-1}). In contrast, agrihortisilviculture had slightly lower C stock (19.20 Mg C ha^{-1}) (Fig. 4). It is observed that overall mean soil C stocks of 23.65 Mg C ha^{-1} are stored across AF systems in the Indian agricultural landscape. The effect size analysis shows that agrihorticulture resulted in the highest soil carbon sequestration with a mean effect of + 31.64% compared to non-agroforestry practices (Fig. 5). Similarly, agrihortisilviculture, agrisilviculture, and silvipasture also had significant influence over C sequestration with a mean effect of + 27.23, +25.43 and 24.62% respectively. All the results were statistically significant. Thus, all the AF systems showed a positive impact on improving soil C stocks.

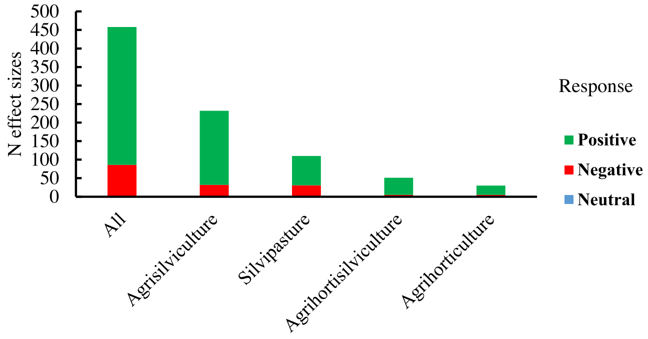


Fig. 3. Number of effect sizes of soil C stocks in response to AF systems.

3.3. *Impacts of land-use change on soil C sequestration in AF systems*

Transition to agroforestry systems significantly influenced C sequestration and increased soil carbon stock by + 25.34% (Fig. 6b). The highest change in C sequestration was observed when converting from grassland to agroforestry with an increase in C stock by + 37.93%. Changes from pasture to agroforestry systems also showed a positive and significant influence, with a + 33.57% increase in soil C stocks (Fig. 6b). Similarly, conversion from agriculture and uncultivated lands towards agroforestry also indicated C sequestration higher by + 28.46 and + 18.01% respectively. In contrast, the shift from forestry to agroforestry practices negatively influenced C sequestration and resulted in a –23.42% reduction in soil carbon stock (Fig. 6b).

3.4. *Performance of agroforestry systems in different climate zones*

The analysis of effect size shows a significant difference in C sequestration among different climate zones considered in this study (Fig. 7a). Overall, AF systems showed outstanding performance in semi-arid subtropical regions, with + 17.13% higher C sequestration than in humid subtropical areas (Fig. 7b). Similarly, the implementation of agroforestry under semi-arid climate also had increased + 9.88% more C sequestration compared to humid subtropical regions (Fig. 7b). Further, specific AF system-wise analysis indicated that the agrisilviculture system had highest C sequestration potential under semi-arid climatic conditions. In contrast, agrihorticulture and silvipasture performed better under semi-arid subtropical regions (Fig. 8b). However, humid subtropical and semi-arid climatic conditions had a negative and significant effect in silvipasture and agri-horticultural system with −15.04% and −14.4% decrease in soil C stocks respectively (Fig. 8b).

3.5. *Impact of varying depth and age of the AF system on soil C stocks*

3.5.1. *Age*

The C sequestration potential and C stock under AF systems vary with the age (duration) of the systems. The effect size analysis showed that soil C sequestration under agroforestry increases along with the age of the system and reaches a peak during the age range of 10–20 years after the conversion of AF systems with a + 39.51% increase (Fig. 9b.). However, as the duration of the AF systems increases, it starts declining gradually. Further, the specific AF system-wise analysis indicated that the highest C sequestration in agrihortisilvicuture occurs during the initial 10 years after conversion. In the case of silvipasture and agrihorticulture, maximum soil C sequestration was observed between the 10–20 years after conversion. Conversely, agrisilviculture had the highest C sequestration potential between 20 and 50 years after conversion (Fig. 9b).

3.5.2. *Soil depth*

AF systems significantly differ in soil C sequestration under varying depths. Our result showed that overall, a significant increase in soil C stocks was found in the upper soil layer (up to 30 cm) with a mean effect ranging from + 30.62% to + 32.74% (Fig. 10b). However, as the depth increases, the soil C sequestration decreased slightly. Silvipature has been the most influential AF system in the top soil layer (0–15 cm) with a

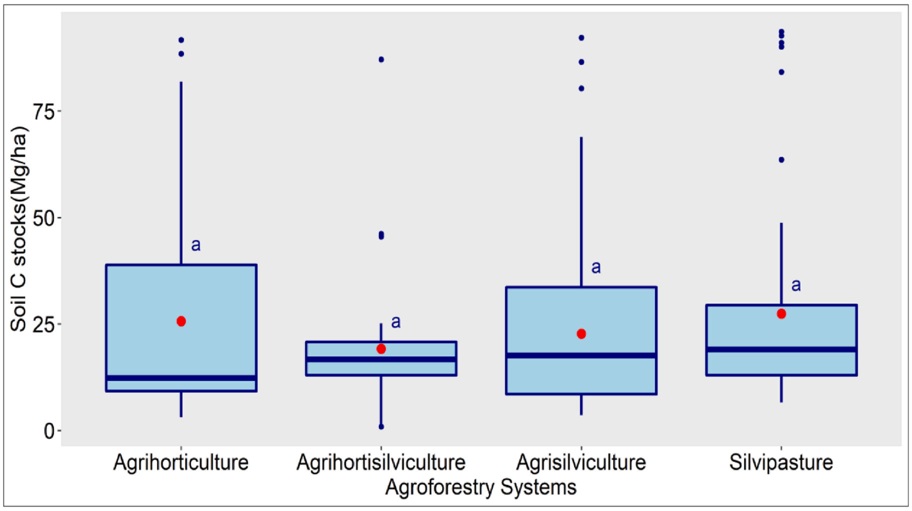


Fig. 4. Soil C stock in different agroforestry systems of India. The red circles denote mean values, and letters indicate significant differences among different agroforestry systems (At 0.05 level of significance). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

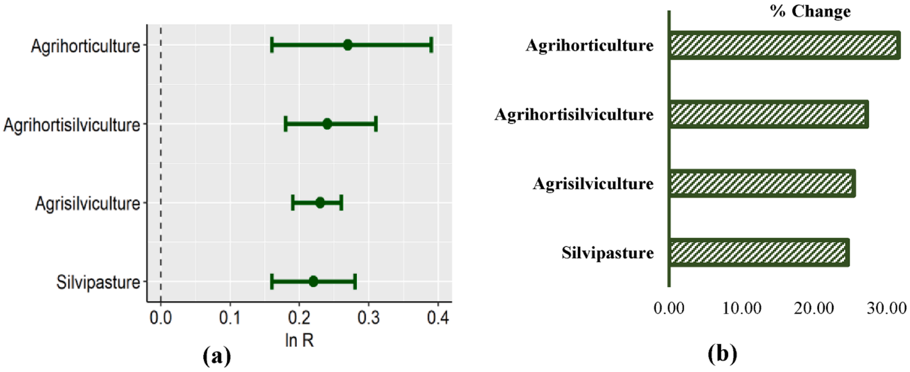


Fig. 5. Effect of AF systems on Soil C stocks. Figure (**a**) shows the effect size, and figure (**b**) shows the percentage change in Soil C stocks. The effect size is significant when CI does not overlap with zero.

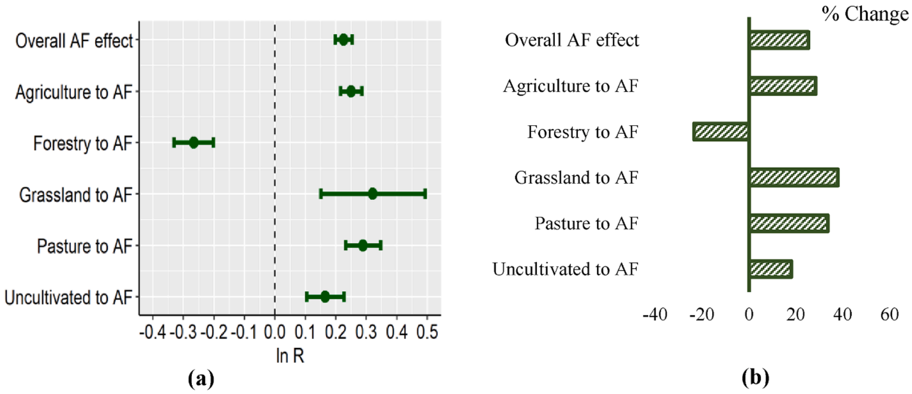


Fig. 6. Effect of land-use changes on soil C stocks. Figure (**a**) shows the effect size, and figure (**b**) shows the percentage change in Soil C stocks. The effect size is significant when CI does not overlap with zero.

mean effect of + 177.29%. Similarly, agrihortisilviculture and agrihorticulture also sequestered more soil C at the upper layer of the soil. However, agrisilviculture has stored more soil C in a soil layer of 15–20 cm depth (Fig. 10b).

3.6. *State-wise C sequestration potential in AF systems*

The state-wise area under different agroforestry systems and C sequestration potential is presented for each climatic zone in India (Table 2.). The relative change in C stock for each AF system along with states was estimated. By multiplying the relative change in the C stock

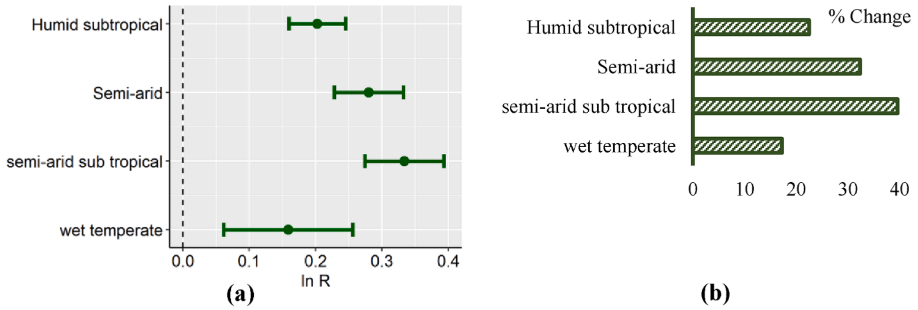


Fig. 7. Mean effect of AF systems on soil C stocks under different climates. Figure (**a**) shows the effect size, and figure (**b**) shows the percentage change in Soil C stocks. The effect size is significant when CI does not overlap with zero.

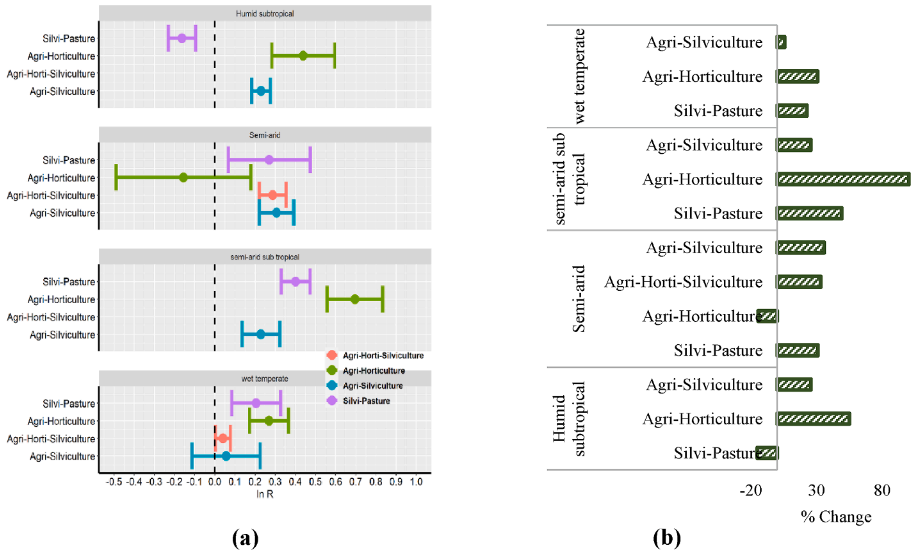


Fig. 8. Mean effect of specific AF systems on soil C stocks under different climates. Figure (**a**) shows the effect size, and figure (**b**) shows the percentage change in Soil C stocks. The effect size is significant when CI does not overlap with zero.

coefficient with area per state, the C sequestration potential in AF systems in the agricultural landscape of India was estimated. The total additional soil C sequestration from AF systems is estimated as 72,81,320 Mg C yr^{-1} (Table 2.). This is an optimistic estimate, as it does not consider the emission of other greenhouse gases. Additionally, the actual amount of C sequestration is based on tree characteristics, agronomic management, and agroecological factors. Furthermore, the Indo-Gangetic plains and Southern plateau & hill regions have a higher potential to capture the atmospheric C through implementing AF systems in India.

3.7. Drivers of soil C sequestration in AF systems

The General Linear Mixed Effect model, as described by equation (4), was employed to determine the factors that affect the C sequestration potential in AF systems. The coefficients of estimates are given in Table 3. The significant fixed covariates indicated by our model are the current AF system, land use prior to implementation of AF systems, age of the AF systems (Time), and rainfall. Interestingly, the climatic zones were not found significant in our model. The model explained 73% of the variability in the data, which is better for an environmental model. Thus, the type of current AF system, age, land use prior to the adoption of the AF system, and rainfall are the major drivers of soil C sequestration in agroforestry.

3.8. Economic assessment

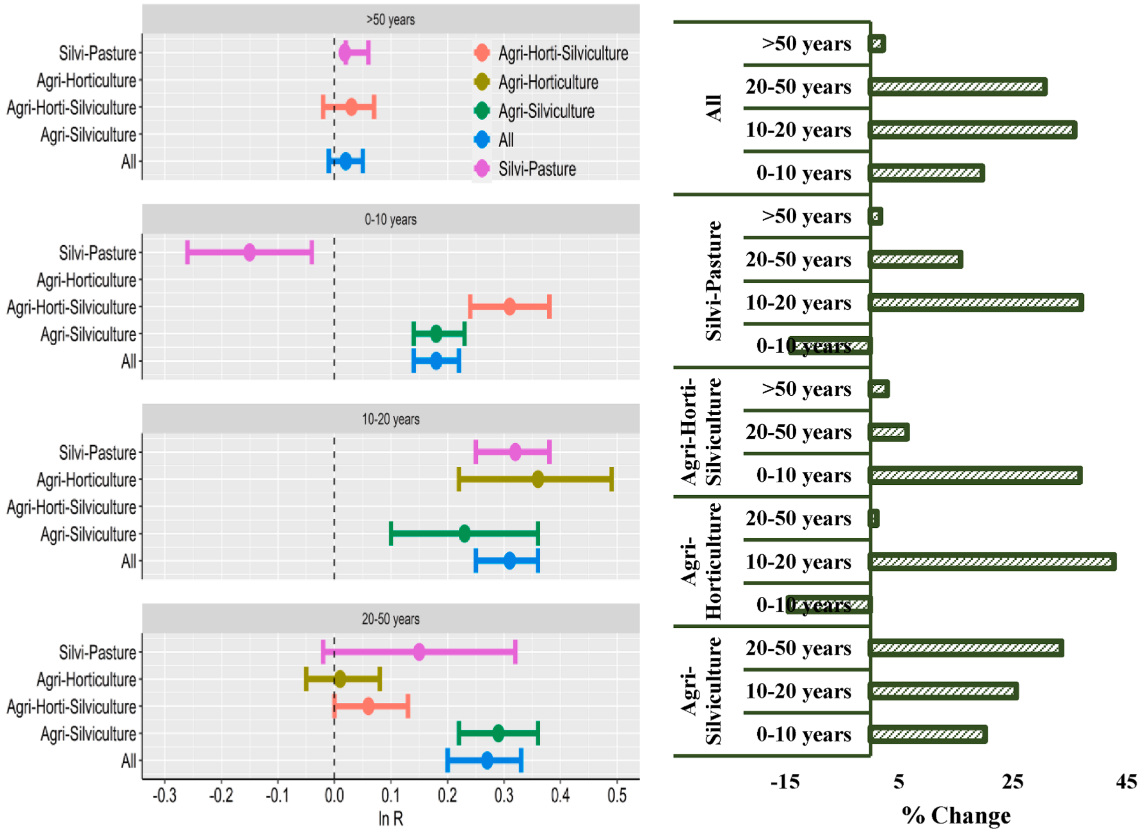
In addition to mitigating climate change, our study shows that agroforestry enhances farmers' income, mainly small-scale and marginal farmers. Our study found that AF systems were economically viable and had the potential to participate in carbon markets. On average, the relative C credit gain from the AF system is estimated at US $100.26 ha^{-1} year^{-1}(Table 4.). Furthermore, the system-wise analysis indicated that additional carbon credit realized from Agrisilviculture, Silvipasture, Agrihortisilviculture, and Agrihorticulture is estimated as 167.26, 116.28, 108.80, and 68.99 US$ ha^{-1} year^{-1}respectively (Table 4). Further, if we account for the stabilization cost, all the AF systems still showed positive net economic return, ranging from US $160.63 to 66.25 ha^{-1} year^{-1}.

The analysis based on the current voluntary carbon market price revealed that net returns are 18 times lower than the price required by 2030 to achieve Paris Agreement's temperature target (US$160/Mg CO$_2$e). As a result, the relative net economic gain is estimated at US$125 ha^{-1} year^{-1} to US$304 ha^{-1} year^{-1}(Table S2). Overall, the current market price results in a significant gap of US$182 ha^{-1} year^{-1} in net returns compared to the required price.

4. Discussion

4.1. Soil C sequestration potential of agroforestry systems

AF systems can be targeted as one of the promising climate-smart



(a) **(b)**

Fig. 9. Mean effect of changes in soil C stock in specific AF systems according to the age of the system. Figure (**a**) shows the effect size, and figure (**b**) shows the percentage change in Soil C stocks. The effect size is significant when CI does not overlap with zero.

farming approaches to address climate change impacts on agriculture. Our results revealed that agroforestry systems positively influence soil C sequestration in Indian agriculture. A plethora of studies confirmed similar results that integrating trees into cropland has improved the soil C stocks (Haile et al., 2008; Nair et al., 2009; Chatterjee et al., 2018; Shi et al., 2018). The increase in carbon sequestration is mainly due to an increase in the quantity as well as the quality of biomass production, changes in dynamics of soil C sequestration, and optimum utilization of growth inputs compared to mono-crops (Jobbágy and Jackson, 2000; Lal, 2001; Nair et al., 2010). However, the rate of C sequestration mainly depends on AF systems and agroecological factors (Albrecht and Kandji, 2003). Further, results show that agrihorticulture had more soil C sequestration potential (+41.28%) than other AF systems. This increase in soil carbon stocks in agrihorticulture is possibly due to high tree density and litter inputs that contribute to the highest C sequestration than other AF systems (Islam et al., 2015). In contrast, despite the highest tree density, the C sequestration potential was lowest in silvipasture. This is because soil C sequestration in silvipasture is primarily influenced by the grasses than the trees, and the former has less potential than the latter (Upson et al., 2016).

Our study indicated that the overall transition to agroforestry systems positively influences soil C sequestration, leading to higher soil C stocks. The highest soil C sequestration was observed with the transformation of grassland to AF systems in comparison with other types of land use change. This is because grasslands have higher organic matter accumulation than trees, resulting in higher soil C levels due to the presence of recalcitrant elements (Jobba'gy and Jackson, 2001). However, De Stefano et al., (2018) observed that converting grassland/pasture to agroforestry had no significant influence on soil C sequestration at 0–30, 0–100, and 0 ≥ 100 cm soil depth. On the contrary, our study found that converting forestland to agroforestry has significantly reduced soil C stocks. This trend was anticipated as AF involves changes in land use and requires clearing of forest, which leads to loss of soil carbon as forest land tends to store its maximum soil carbon stocks in the upper layer of soil; thus, the transition from forest to AF systems particularly agriculture leads to a decrease in the soil carbon stock (Guo and Gifford, 2002; Leuschner et al., 2013). De Stefano et al., (2018) also observed similar findings and highlighted that conversion from forest to agrisilviculture had decreased soil C sequestration by −12%. Therefore, it is crucial to consider the implications of converting natural forests for agroforestry for a sustainable solutions to climate change, and therefore, continuous monitoring is needed to minimize the trade-offs in the conservation and livelihood goals. Our findings also highlighted that conversion from cropland to AF systems had significantly higher soil C sequestration. Availability of higher inputs, minimal soil disturbance, residue retention, and reduction in the rate of decomposition could be the possible explanation for higher C sequestration (Aslam et al., 1999; Post and Kwon, 2000; Montagnini and Nair, 2004).

4.2. Impacts of climate, age, and soil depth on C sequestration potential of AF systems

The relative changes in soil C potential of AF systems depend on prevailing climatic conditions. Climate plays a critical role in soil C sequestration as it regulates the production mechanism of soil biomass and microbes (Callensen et al., 2003). Overall, AF systems implemented in semi-arid subtropical climates had significantly higher soil C stocks, possibly due to less soil organic carbon in these areas than in humid subtropical climates (Mureva et al., 2018). Agrihorticulture and silvipasture systems have shown more soil C sequestration in semi-arid

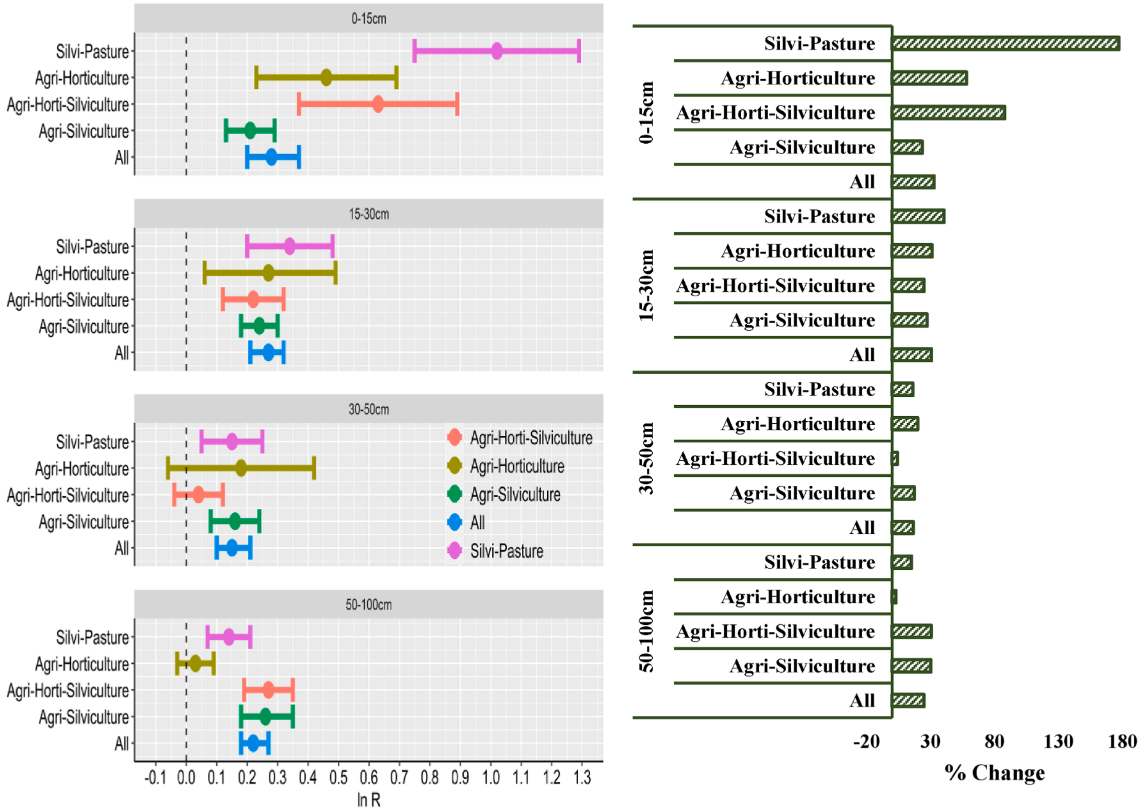


Fig. 10. Mean effect of changes in soil C stock in specific AF systems according to the depth of the system. Figure (**a**) shows the effect size, and figure (**b**) shows the percentage change in Soil C stocks. The effect size is significant when CI does not overlap with zero.

Table3
Estimates general linear mixed model on C sequestration potential of AF systems with non-AF practices.

Coefficients	Estimate	Std. Error
Intercept	1.87	0.44
AF systems**		
Agrihosrtisilviculture	0.06	0.07
Agrisilviculture	0.16	0.07
Silvipasture	0.17	0.07
Climate		
HumidSubtropical	0.41	0.21
Semi-arid	0.21	0.16
Semiarid subtropical	0.32	0.18
Land use before AF systems***		
Forest	−0.23	0.19
Grassland	−0.35	0.07
Pasture	−0.25	0.06
UncultivatedLand	−0.17	0.05
Age of the AF system***		
10–20 yr	0.44	0.07
20–50 yr	0.27	0.06
>50 yr	0.24	0.09
Rainfall***	−0.32	0.07
R^2m	0.43	
R^2c	0.73	
AIC	−58.5	
BIC	9.1	
n	423	

Note: ***, **, and ** indicate 1, 5, and 10 percent levels of significance.

subtropical climates due to higher tree density, biomass, and growth rate (Shi et al., 2018). However, agrisilviculture had shown higher C sequestration potential in semi-arid climates, which may be attributed to a congenial environment for the formation of pedogenic $CaCO_3$ in semi-arid conditions (Srinivasarao et al., 2014). Tsonkova et al., (2012) also highlighted similar findings in alley cropping in tropical climates. They indicated that rapidly growing trees with high nitrogen fixation are the possible reasons for higher C sequestration.

The age of the tree also determines the rate of change in soil C sequestration in agroforestry. In this study, the soil carbon sequestration in AF systems varied according to the age of the system. Younger trees (up to 20 years) had higher soil C stocks and sequestration potential than older trees. Shi et al., (2018) also witnessed a similar trend of higher C sequestration in younger trees. The higher soil C stocks observed in younger trees are possibly due to the adoption of rapidly growing tree species, which increases the litter quantity and vegetation and thereby increases the accumulation of soil C (Singh and Gill, 2014; Cardinael et al., 2017). On the contrary, Takimoto et al., (2008) observed that combining trees in cropland leads to a lower C sequestration during the initial planting stage.

Soil depth is another critical factor that affects the C sequestration potential of AF systems. The *meta*-analysis highlighted that changes in soil C stocks were more prominent in the upper layer of the soil. The findings showed higher soil C stocks in the topsoil (up to 30 cm), whereas it decreased in the deeper layer of the soils. This is mainly due to more accumulation of litter inputs from the trees and crops at the upper layer, whereas deeper soils have lower biomass (Das et al., 2022). Similar results are also observed by Shi et al., (2018), Chatterjee et al., (2020), and Das et al., (2022).

4.3. *Drivers of soil C sequestration*

Multiple factors govern the soil C sequestration potential of AF systems. Our result shows that the current AF system implemented, land use before the adoption, rainfall, and tree age were the major factors that determine the C sequestration potential in agroforestry systems in the Indian agricultural landscape. The process of carbon sequestration is dynamic, not static, and mainly hinges on soil, plant, system

Table 4
Effect of AF Systems on soil C stock, C credit, and economic cost and returns.

Agroforestry Systems	Relative Change in C stock (Mg C ha^{-1} year^{-1}) ***		CO$_2$ equivalent (Mg CO$_2$ ha^{-1} year^{-1})	Carbon credit (US$ ha^{-1} year^{-1})	N input to stabilize C storage (N Kg ha^{-1} year^{-1})	N cost to stabilize C storage (US$ ha^{-1} year^{-1})	Economic Return (US$ ha^{-1} year^{-1})
	Mean	95% CI					
Agrisilviculture	0.53	0.25 to 0.81	1.94	167.26	37.96	6.64	160.63
Agrihorticulture	0.22	0.13 to 0.31	0.80	68.99	15.66	2.74	66.25
Agrihortisilviculture	0.35	0.25 to 0.44	1.27	108.80	24.69	4.32	104.48
Silvipasture	0.37	0.23 to 0.51	1.35	116.28	26.39	4.61	111.67
Overall AF	0.32	0.14 to 0.50	1.17	100.26	22.75	3.98	96.28

Note: *** Indicate 1% level of significance.

characteristics, and farm management practices (Feliciano et al., 2018). In addition, agroecological conditions in which the AF system is adopted also affect the C sequestration process. However, the current regression model failed to account for the effect of different climatic conditions on carbon sequestration. This requires further in-depth research by developing different climate change scenarios influencing AF systems and C sequestration. Conversion of forestland to the AF system negatively affected C sequestration, whereas conversion of grassland and pasture leads to more C sequestration. Furthermore, adequate precipitation is crucial to enhance the carbon sequestration process, as it expedites microbial growth and decomposition (Lai et al., 2013).

4.4. Economic assessment

Nature-based solutions are recognized as economically feasible and environmentally sustainable solutions to address the detrimental impacts of climate change. The valuation of ecosystem services is crucial as it provides monetary incentives for implementing sustainable agricultural practices (Daily, 1997). Additionally, it helps to prioritize the resource allocation towards the most cost-effective technologies and helps in the quantification of economic benefits from emission-reducing and carbon storage practices. Further, valuation also helps policy decision-makers in climate change mitigation (Valatin, 2014). Agroforestry is widely acknowledged as a sustainable approach to ensure socio-economic and environmental development, mainly in tropical and subtropical regions (Ramesh et al., 2015; Muchane et al., 2020). Our findings highlighted that AF systems could be considered economically viable C sequestration practices, as the net return was higher in all the AF systems considered in this study. These systems have the potential to generate additional C credit worth 68.99 to 167.26US$ha^{-1} year^{-1}. Further, Payment for Ecosystem Services (PES) should be given to smallholders for C sequestration through agroforestry. In this direction, several countries have already implemented carbon taxes to reward farmers for C sequestration in agriculture (Baah-Acheamfour et al., 2017). However, accurate measurement of soil carbon stock in fields is necessary to make more economically viable AF systems (Walcott et al., 2009).

Our study also highlighted the significant disparity between the current market price and the price required to achieve net zero emissions by 2050. According to the recent analysis by Wood Mackenzie and Network for Greening the Finance System (2021), for limiting global temperature rise to 1.5°Crequires a significant increase in carbon support prices to the tune of US$160 per Mg of CO$_2$ by 2030. This indicates a huge opportunity for farmers to tap the carbon credit markets by implementing agroforestry systems. However, a major challenge is the limited knowledge about the environmental benefits of improved practices and the existence of carbon markets among the farming community. In addition, the process of individual participation in the carbon market is a complex process and requires in-depth market knowledge. Nevertheless, creating awareness of carbon market-related programs and linking village-level farmer communities, such as FPOs and Co-operatives, with carbon trading companies facilitates participation.

5. Conclusions and policy implications

To achieve the goal of Paris Agreement of restricting global warming to 1.5 °C, a substantial reduction in greenhouse gas emissions is necessary. In this regard, our study found that AF systems have the potential to revert the climate change impacts on Indian agriculture. A comprehensive *meta*-analysis was performed to identify the AF systems, land use change, climate, age, and soil depth to identify the drivers of C sequestration in agroforestry. The study concludes that AF systems had higher soil C sequestration potential than non-AF systems. Agrihorticulture is the most effective AF system in terms of higher C sequestration. However, the transition from forest to agroforestry negatively influenced carbon sequestration, highlighting the need for careful evaluation of consequences and trade-offs when converting the natural forest to agroforestry for a sustainable solution to climate change. The change in soil carbon stocks and sequestration potential of the AF system is determined by the type of AF system implemented, land use before implementation, tree age, and rainfall. All the AF systems considered in this study were found economically profitable and provided an opportunity for carbon trading to smallholders. Furthermore, agroforestry can be imperative in achieving India's climate target (creating an additional carbon stock of 2.5–3 billion tons of CO$_2$eby 2030) and a net zero emission target by 2070. Therefore, it is crucial to promote agroforestry practices by offering economic incentives for providing ecosystem services to smallholders. Further, steps need to be taken to strengthen the value chains of agroforestry systems through training, demonstration, and appropriate policy prescription. This study thus shows AF systems have the potential to address the climate change impacts as well as sustainability issues in the Indian agricultural landscape.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2023.101537.

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