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Carbon storage and economic efficiency of fruit-based systems in semi-arid region: a symbiotic approach for sustainable agriculture and climate resilience

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Abstract

Enhancing our understanding of carbon (C) stock in diverse horticulture and fruit-based agroforestry systems has potential to provide farmers with supplementary advantages in terms of poverty alleviation and livelihood development which can significantly benefit C market initiatives like UN-REDD (reducing emissions from deforestation and forest degradation). Therefore, the current study aimed to assess the biomass accumulation, C storage and economic efficacy of seven agro-ecosystems, namely guava-based agri-horticulture system (AHS), mango-AHS, guava- pure orchard (PO), mango-PO, Indian gooseberry -PO, teak boundary plantation (TBP) and annual cropping system (ACS) under two different landscape positions viz., upland and lowland in the semi-arid region of Vindhyan ranges. The result indicated that mango-AHS accumulated significantly ($p < 0.05$) higher biomass (26.01 t ha^{-1}) and vegetation C density (13.01 t C ha^{-1}) whereas, soil (35.23 t C ha^{-1}), litter (0.64 t C ha^{-1}), and total C density (46.63 t C ha^{-1}) was maximum under mango-PO closely followed by mango-AHS. The guava-PO system exhibited significantly ($p < 0.05$) higher C sequestration (2.11 t C ha^{-1} yr^{-1}), and CO_2 abatement (7.76 t CO_2 ha^{-1} yr^{-1}) rate compared to other systems with C credit generation of 129.76 US\$ ha^{-1} $year^{-1}$. However, mango-AHS was the most lucrative system providing net returns of 4835.48 US\$ ha^{-1} yr^{-1} and 5.87 benefit–cost ratio. The C credits help in getting farmers an additional income; however, the economic impact of C credit was low (1.16–6.80%) when weighed against the overall economic efficacy of the different systems. Overall, the study concluded that farmers in the region should adopt fruit-based systems, especially agroforestry systems to establish mutually beneficial relationships between mitigation of climate change and livelihood stability.

Highlights

- Fruit based systems can sequestrate up to 2.11 t carbon per hectare per year.
- Tree-based perennial systems were about five times more lucrative than annual cropping system.
- Tree-based systems can earn an additional 7 % of total revenue via carbon credits.

Keywords Agroforestry systems, Carbon credit, Biomass accumulation, Carbon sequestration, Economic efficacy

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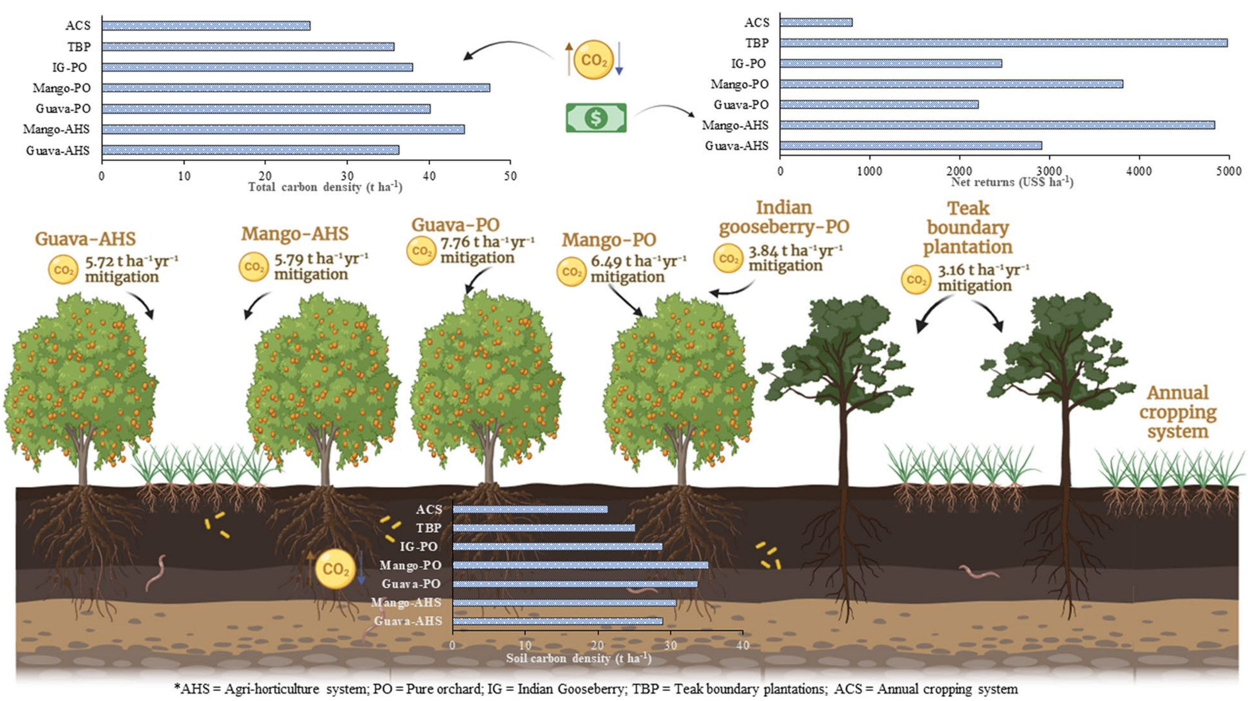
Graphical Abstract



1 Introduction

Internationally, global warming and climate change have emerged as major challenges impinging upon the sustainability of the agro-ecosystems (Bhardwaj et al. 2021), especially with adverse impact on farm productivity (Reppin et al. 2020). The mean global air temperature has already increased 1.53°C from the pre-industrial period (IPCC 2019) and is expected to climb 1.4 – 5.8°C by 2100 (Cubasch et al. 2013). Simultaneously, world's population is increasing rapidly, and it is anticipated to reach 9.7 billion by 2050 (UN 2015), which is 34% higher than the current population; that is affecting people's food and livelihood security (Sharma et al. 2023). In India, wherein over 70% of the population resides in rural areas and sustains their livelihood through agricultural activities (Adhikari et al. 2020), climate change increases vulnerability among small and medium marginal land-holding farmers (Kumara et al. 2023).

Under above-said context, it becomes imperative to embrace nature-based farming systems, especially emphasizing agroforestry systems (AFS) which incorporate perennial trees on farmlands. AFS are implemented with the primary objective of achieving economic benefits to meet the growing demands of the country and the livelihood requirements of rural communities (Adhikari et al. 2020). Moreover, agroforestry (AF) also performs an important part in alleviating and adopting the detrimental effect of climate change because of its capacity to hold enormous quantities of carbon (C) over long periods (Panwar et al. 2022). It is noteworthy, AF comprehends a wide range of practices extending from simple systems such as improved fallows in shifting cultivation and silvopastoral to complex agroforests, namely alley cropping and home gardens practiced throughout the globe from Arctic to south temperate regions (Sharma et al. 2023). Globally, over 20% of the population (1.2 billion) rely on the diversified ecosystem services offered by AFS, especially in developing nations (Watson et al. 2000) with a C abatement potential of 1.1–2.2 Pg C in the coming five decades (Solomon et al. 2007). Furthermore, AF is also recognized as a highly effective and cost-efficient approach to tackle concerns such as changing climate, degradation of land, food security, pollution and to prevent environmental damage in accordance with Kyoto Protocol and several international accords (Chavan et al. 2022). In recognition of pivotal importance of agroforestry, India adopted National Agroforestry Policy 2014, with the specific objective of propelling the widespread dissemination of agroforestry practices. Simultaneously, as a part of its nationally determined contribution to the Paris Climate Agreement, Indian Government has committed to sequestrate an additional 2.5 - 3.0×10^9 t CO_2 equivalent (eq) by 2030, which can only be accomplished by integrating trees on farmlands (Panwar et al. 2022). Moreover, under Kyoto protocol (Clean Development Mechanisms), C stored in AFS which have recently been sequestrated alongside agricultural systems, are recognized and eligible for sale to industrialized countries as a means to mitigate their C emission while drive is also on to include soil C as well (Lal 2004; Zahoor et al. 2021). Thus, gaining a comprehensive understanding of ability of AFS and orchards to store C offers advantages to the farmers in terms of poverty alleviation and livelihood enhancement through the C market initiatives, like $REDD^+$ (Naik et al. 2021). REDD is basically an abbreviation for "reducing emissions from deforestation and forest degradation", followed by "plus" referring to "the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries". In fact, the main goal of $REDD^+$ programme, which is a component of the United Nations Framework Convention on Climate Change, is to undertake national government initiatives to reduce human pressure on forests that result in greenhouse gas emissions at the national level. Therefore, many initiatives have a growing global focus on AF, primarily driven by the recognition of AF's importance in addressing changing climate through adaptation and mitigation strategies (Jose and Bardhan 2012).

Hence, AF practices, especially fruit-based AFS, have been widely embraced by resource-constrained farmers in various regions of the country due to their high market value and nutritional significance (Zahoor et al. 2021); moreover, it also provides sustainability within agroecosystems (Adhikari et al. 2020; Sharma et al. 2022). It is important to mention that the efficiency of biomass production and C sequestration varies across the different AFS. This variability in the biomass accumulation/ C sequestration potential of AFS is associated with numerous factors, such as plant attributes (plant species, tree density alley crops, and age), climatic variability and system properties (structure, functions, and management) (Adhikari et al. 2020). In the past, various studies have assessed the biomass accumulation and C storage capacity of the AFS but is limited to the commercial important trees species such as *Populus deltoides* and *Eucalyptus* sp. (Chauhan et al. 2010; Chavan et al. 2023; Dhyan et al. 2016) or fruit-based systems, particularly limited to the Himalayan (Rajput et al. 2015, 2017; Zahoor et al. 2021) or tropical region (Das et al. 2022; Ganeshamurthy et al. 2020, 2019). Thus, a paucity of information exists concerning the potential for biomass production, C storage, and economic efficiency of fruit-based AFS, especially in Indo-Gangetic plains. Moreover, Baah-Acheamfour et al. (2016) have stressed on conducting further research to validate patterns across different geographical areas, determine the potential for growth of alternative food systems at a regional level, and evaluate their sustainability and the potential abatement of greenhouse gas (GHG) emissions on a regional or national scale, since, a more comprehensive evaluation of the overall C stocks and economic valuation in AF land use systems necessitates the inclusion of national explicit assessments (Goswami et al. 2016; Zahoor et al. 2021). Simultaneously, it is crucial to assess the precise C fluxes resulting from patterns of land use change to get a comprehensive understanding of the dynamics and patterns of land use within a specific geographic area that may assist administrators and policymakers in preparing effective and strategic solutions for mitigating climate change.

Therefore, the current investigation aimed to evaluate the biomass accumulation, C storage and sequestration rate, and economic efficacy of AFS in the Vindhyan region of Indo-Gangetic Plains, considering the facts described above. The study's objectives were: (i) quantification of biomass accumulation and C density under prevalent perennial tree-based systems in Vindhyan region agro-ecosystem, (ii) assessing the C sequestration and CO_2 abatement rate in prevalent perennial agro-ecosystem, and (iii) valuing the economic efficacy of the system including the potential for C credit generation. The findings will have significant implications for policymakers and farmers pertaining to selection and promotion of suitable AFS for C budgeting and generating income in Indo-Gangetic Plains.

2 Materials and methods

2.1 Experimental area

The investigation was conducted in RGS-Campus of Banaras Hindu University, Mirzapur, and the surrounding area situated at 25^0 5'—25^0 6' N and 82^0 35'—82^0 59' E, at an elevation ranging from 81–360 m above mean sea level, within the middle Indo-Gangetic Plains (Fig. 1a). The study area falls within agro-climatic zone III A, which is classified as semi-arid eastern plain zone, characterized by inconsistent precipitation and low soil quality. The regional climate is characterized by semi-arid to sub-humid, and the hottest months were May and June (31.08–36.05 °C), whereas the coldest months were December and January (13.8–18.6 °C). The monthly maximum relative humidity ranged from 90.20% to 94.68%, while the minimum ranged from 55.36% to 72.81%. The area received yearly precipitation of 1068.55 mm yr^{-1},

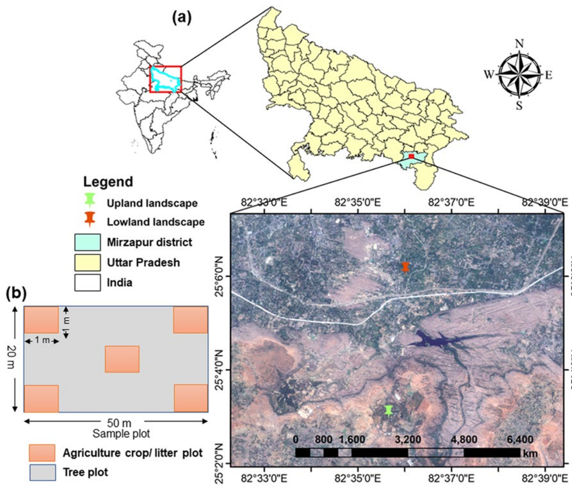


Fig. 1 Map of the (**a**) study area and (**b**) sampling plot design

with about 88% occurring between June and September. The average potential evapo-transpiration rate was 6.45 mm day^{-1} (Sharma et al. 2022).

2.2 Experiment details

The present study was conducted in a two-factor randomized complete block design, each replicated threefold. The factor-I consists of seven distinct land use systems (Table 1a), encompassing two AFS, namely guava (*Psidium guajava* L.)-based agri-horticulture systems (AHS) and mango (*Mangifera indica* L.)-based AHS; three pure orchard (PO) systems, viz., Indian gooseberry (IG) (*Phyllanthus emblica* L.), mango and guava; and one teak (*Tectona grandis* L.) boundary plantation (TBP) and annual cropping system (ACS) each. In guava and mango-AHS, the mungbean (*Vigna radiata* (L.) R. Wilczek, cv. Samrat) followed by wheat (*Triticum aestivum* L., cv. HD 2967) were cultivated as an annual alley crop. Similarly, in ACS, the mungbean (cv. Samrat) *fb* wheat (cv. HD 2967) crops were grown. Guava in AHS and PO systems was spaced at 7 m × 7 m and 6 m × 6 m, respectively; whereas, mango in PO and AHS was spaced at 9 m × 9 m, and 10 m × 10 m spacing, respectively. IG-PO was also spaced at 10 m × 10 m. However, in TBP, across the bunds of rice [*Oryza sativa* cv. BPT 5204 (samba mansuri)] – wheat (cv. HD 2967) field, teak trees were planted in two rows at 2.5 m × 2.5 m spacing. The average age of guava-AHS and guava-PO was approximately seven years, while the mango-AHS, mango-PO, IG-PO, and TBP were about 12 years old. The factor-II consists of two landscape positions, namely upland and lowland.

2.3 Observation

2.3.1 Tree biomass

The present study undertook biomass estimation through a systematic approach involving laying down plots of 50 m × 10 m. All of the trees inside the specified plot were enumerated, followed by measurement of diameter [at breast height (dbh)], and height measurements were performed using calipers and Ravi's multimeter, respectively. For those species, where the volume equation was unavailable, the form factor was determined utilizing Spiegel Relaskope to estimate the volume of tree (Bitlerlich 1984; Pressler 1895) with values of specific gravity obtained from the extant literature sources. In cases where specific gravity values were unavailable, cores of the stem were collected to ascertain the specific gravity that was subsequently utilized to calculate stem biomass using maximum moisture method (Smith 1954). The biomass for guava, mango, IG and teak trees was determined using equation developed by Brown (1997).

$$Y = \exp\{-1.996 + 2.32 \times \ln(\text{dbh})\}$$

where, Y = Above − ground biomass (AGB, kg); dbh in cm

Table 1 Structures and composition of prevalent cropping systems in semi-arid region of Vindhyan range

Major systems	Tree/crop combination	Abbreviation	Spacing		No. of trees (ha^{-1})	Age of woody perennial (years)
			Woody perennials (m)	Intercrops (cm)		
Agri- horticulture systems (AHS)	Guava + Mungbean *fb* wheat	Guava-AHS	7 × 7	30 × 10 & 22.5 × 5	205	7
	Mango + Mungbean *fb* wheat	Mango-AHS	10 × 10	22.5 × 5	100	12
Pure orchard (PO)	Guava	Guava-PO	6 × 6	-	277	7
	Mango	Mango-PO	9 × 9	-	123	12
	Indian gooseberry (IG)	IG-PO	10 × 10	-	100	12
Boundary plantation	Teak + Rice *fb* wheat	TBP	2.5 × 2.5	20 × 10 & 22.5 × 5	80	12
Annual cropping system (ACS)	Mungbean *fb* Wheat	ACP	-	30 × 10 & 22.5 × 5	-	-

fb followed by

To calculate below ground biomass (BGB) of trees, AGB was multiplied by subsequent root–shoot ratio (Mokany et al.2006). The total tree biomass was ascertained by adding AGB and BGB.

2.3.2 Agricultural crop biomass

To estimate herbage biomass (including annual crop plus weeds) under AHS and ACS, the herbage samples were collected at the physiological maturity of the crop and biomass was ascertained according to methodology described by Verma et al. (2023c) utilizing quadrat of size 1 m × 1 m placed at five randomly selected spots in main plot (Fig. 1b).

2.3.3 Litter biomass

The litter biomass (t ha^{-1}) in each land use system was determined through litter traps (1 m × 1 m size) made of nylon netting (1 mm diameter mesh), positioned about one meter above the ground under the canopy of five randomly selected trees (Fig. 1b). The litter collected from the traps was subsequently subjected to an oven drying process at 60°C, until a state of consistent weight was attained to calculate the litter biomass.

2.3.4 Carbon density and sequestration capacity

The vegetation C density (t C ha^{-1}) was determined by multiplying total biomass by 0.5 (conversion factor) (Penman et al. 2003), whereas, the litter C density was ascertained by multiplying litter biomass by 0.37 (Woomer 1993). The bulk density and soil organic carbon (SOC) were assessed using core sampler technique (Blake and Hartge 1986) and modified Walkley and Black (1934) method, respectively, while soil C density (SCD) was calculated through approach outlined by Nelson and Sommers (1996).

The total C density (TCD) was estimated by adding carbon density of vegetation, soil and litter. The C sequestration rate was ascertained by calculating the difference between the C stock of the AHS or PO system and that of the adjoining ACS. This value was subsequently divided by the average age of the tree within the respective systems (Rogelj et al. 2015). The CO_2 abatement rate, on the other hand, was determined by multiplying a coefficient of 3.67 by the aforementioned rate of C sequestration (Pearson et al. 2007).

2.3.5 Carbon credits and system bio-economics

One C credit was assigned to 1 t CO_2 eq mitigated in the form of plant biomass. Consequently, CO_2 abatement rates of retained biomass (ha^{-1} yr^{-1}) in the corresponding systems were used to determine the C credit in a particular land use system considering price of one C credit as US$ 20. In order to calculate cost of cultivation, the study factored in the aggregate investment incurred in production, the value of land within the system, and the cultural management practices. Additionally, the biological productivity was estimated by taking into account the marketable biomass of each functional unit across different land use system which were taken into consideration for estimating the gross returns in US$ ha^{-1} basis. After computing all costs, these were subtracted from the gross returns (US$ ha^{-1}) to obtain the net remunerative (US$ ha^{-1}) for each land use systems. Simultaneously, benefit–cost ratio was determined by dividing the net returns by cost of cultivation.

2.4 Statistical analysis

Data pertaining to each parameter of the land use system under both landscape positions were acquired and analyzed in accordance with the methodology proposed by Gomez and Gomez (1984). The normality of variables under study was determined through Shapiro–Wilk test and Bartlett variance homogeneity test. Two way Analysis of Variance approach was used to evaluate the impact of the land use system and landscape position on C accumulation, C credit and income generation, and subsequently, the F-test was conducted and the critical difference (CD) was determined at 5% significance level ($p < 0.05$) using R studio 2022.07.2 (2022) (with doebioresearch package). Microsoft Excel 2021 was utilized to prepare the graphical representations of the obtained data.

3 Results

3.1 Biomass accumulation

The results from the current investigation revealed that the land use systems significantly ($p < 0.05$) influenced the biomass production potential (Table 2). The significant ($p < 0.05$) maximum AGB was recorded under mango-AHS (22.31 t ha^{-1}) followed by mango-PO (18.39 t ha^{-1}) and IG-PO (14.62 t ha^{-1}), whereas minimum in ACS. The BGB varied significantly among the different land use systems from 3.70 t ha^{-1} (mango-AHS) to 1.08 t ha^{-1} (ACS). Similarly, the substantially highest total biomass was accumulated in mango-AHS (26.01 t ha^{-1}) and followed the order of mango-AHS > mango-PO > TBP > IG-PO > guava-AHS > guava-PO > ACS. Moreover, the litter biomass was also significantly impacted by the land use systems. The highest litter biomass was found in mango-PO (1.74 t ha^{-1}), followed by mango-AHS (1.43 t ha^{-1}) and IG-PO (1.15 t ha^{-1}) (Table 2). The landscape position also had a substantial ($p < 0.05$) effect on the biomass accumulation of various land use systems. The lowland areas have a higher biomass accumulation, including AGB (15.04 t ha^{-1}), BGB (2.94 t ha^{-1}), total biomass (17.98 t ha^{-1}) and litter biomass (0.98 t ha^{-1}) compared to the upland areas. The interaction of land use systems × landscape position also

Table 2 Effect of land use system and landscape position on biomass accumulation in semi-arid region of Vindhyan range

Treatments	Biomass accumulation (t ha^{-1})			
	Above-ground	**Below-ground**	**Total**	**Litter**
Land use systems				
Guava-AHS	11.43 ± 1.42^{d}	2.95 ± 0.39^{bc}	14.38 ± 1.81^{d}	0.41 ± 0.21^{d}
Mango-AHS	22.31 ± 2.43^{a}	3.70 ± 0.41^{a}	26.01 ± 2.84^{a}	1.43 ± 0.19^{b}
Guava-PO	9.85 ± 0.76^{d}	2.56 ± 0.20^{d}	12.41 ± 0.96^{d}	0.41 ± 0.06^{d}
Mango-PO	18.39 ± 2.41^{b}	3.13 ± 0.41^{b}	21.52 ± 2.82^{b}	1.74 ± 0.17^{a}
Indian gooseberry-PO	14.62 ± 1.05^{c}	2.63 ± 0.19^{cd}	17.25 ± 1.24^{c}	1.15 ± 0.12^{c}
TBP	17.59 ± 1.59^{b}	3.60 ± 0.28^{a}	21.19 ± 1.83^{b}	0.07 ± 0.02^{e}
ACS	6.25 ± 1.57^{e}	1.08 ± 0.29^{e}	7.33 ± 1.86^{e}	1.04 ± 0.32^{c}
CD ($p < 0.05$)	1.79	0.32	2.10	0.14
Landscape position				
Lowland area	15.04 ± 5.85^{a}	2.94 ± 0.94^{a}	17.98 ± 6.69^{a}	0.98 ± 0.62^{a}
Upland area	13.66 ± 5.03^{b}	2.68 ± 0.81^{b}	16.34 ± 5.75^{b}	0.81 ± 0.58^{b}
CD ($p < 0.05$)	0.96	0.17	1.12	0.08

AHS Agri-horticulture system, *PO* Pure orchard, *TBP* Teak boundary plantations, *ACS* Annual cropping system, *CD* Critical difference. The values carrying different alphabetical superscripts ($^{a,b,c,d,\cdots}$) within the columns above, differ significantly amongst themselves ($p < 0.05$)

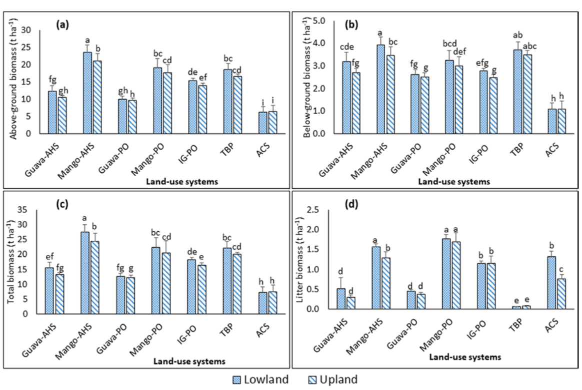


Fig. 2 Interaction effect of land use system and landscape position on the biomass accumulation. Here, (**a**) above ground biomass; (**b**) belowground biomass; (**c**) total biomass; (**d**) litter biomass. AHS = Agri-horticulture system; PO = Pure orchard; TBP = Teak boundary plantations; IG = Indian Gooseberry; ACS = Annual cropping system. The values carrying different alphabetical superscripts ($^{a,b,c,d,\cdots}$) above the bars, differ significantly amongst themselves ($p < 0.05$)

significantly influenced biomass production. The maximum AGB (23.63 t ha^{-1}), BGB (3.93 t ha^{-1}), and total biomass (27.56 t ha^{-1}) were recorded under the mango-AFS × lowland areas, whereas the highest litter biomass (1.78 t ha^{-1}) was observed under the mango-PO × lowland areas (Fig. 2).

3.2 Carbon density

The C density was also observed to vary substantially ($p < 0.05$) across diverse components of land use systems. The maximum vegetation C density was observed under mango-AHS (13.01 t C ha^{-1}) followed by mango-PO and TBP while lowest in ACS (3.67 t C ha^{-1}) (Table 3). Conversely, the highest SOC was recorded under the mango-PO (0.89%), subsequently leading to the maximum SCD under the mango-PO (35.23 t C ha^{-1}) followed by mango-AHS (30.82 t C ha^{-1}) and guava-PO (33.86 t C ha^{-1}). The minimum SOC and SCD were recorded under the ACS (21.37 and 0.46 t C ha^{-1}, respectively). Similarly, the considerably ($p < 0.05$) higher litter biomass was accumulated in mango-PO (0.64 t C ha^{-1}), and followed the order of mango-PO > mango-AHS > ACS > IG-PO > guava-AHS > guava-PO > TBP. The TCD differed considerably ($p < 0.05$) among diverse land use systems, with mango-PO (46.63 t C ha^{-1}) having the maximum TCD, which was statistically identical to the mango-AHS, while the minimum was under ACS (25.42 t C ha^{-1}) (Table 3). The interaction of land use systems × landscape position also had a significant influence on the C density. The highest vegetation C density (13.78 t C ha^{-1}) was recorded under mango-AFS × lowland areas, whereas the highest SCD (38.98 t C ha^{-1}), litter C density (0.66 t C ha^{-1}), and TCD (52.03 t C ha^{-1}) were recorded under mango-PO × lowland areas (Fig. 3).

3.3 C sequestration and CO_2 mitigation rate

The diverse land use systems under consideration substantially ($p < 0.05$) affected the C sequestration rate and CO_2 abatement potential (Table 4). In the vegetation, the mango-AHS was found to be the most efficient for C sequestration (0.78 t C ha^{-1} yr^{-1}), and CO_2 abatement potential (2.86 t CO_2 ha^{-1} yr^{-1}) followed by mango-PO, TBP, guava-AHS, and IG-PO, and least efficient was

Table 3 Effect of land use system and landscape position on carbon density and soil organic carbon in semi-arid region of Vindhyan range

Treatments	Carbon density (t C ha^{-1})				SOC (%) (0–30 cm)
	Vegetation	SCD	Litter	Total	
Land use systems					
Guava-AHS	7.19 ± 0.90^{d}	28.99 ± 5.96^{cd}	0.15 ± 0.08^{d}	36.34 ± 6.79^{bc}	0.69 ± 0.16^{c}
Mango-AHS	13.01 ± 1.42^{a}	30.82 ± 5.39^{bc}	0.53 ± 0.07^{b}	44.36 ± 6.07^{a}	0.74 ± 0.15^{bc}
Guava-PO	6.21 ± 0.48^{d}	33.86 ± 6.74^{ab}	0.15 ± 0.02^{d}	40.22 ± 6.86^{b}	0.83 ± 0.19^{ab}
Mango-PO	10.76 ± 1.41^{b}	35.23 ± 6.04^{a}	0.64 ± 0.06^{a}	46.63 ± 7.12^{a}	0.89 ± 0.18^{a}
Indian gooseberry-PO	8.63 ± 0.62^{c}	28.93 ± 4.37^{cd}	0.43 ± 0.04^{c}	37.98 ± 4.80^{bc}	0.68 ± 0.11^{c}
TBP	10.60 ± 0.91^{b}	25.13 ± 5.52^{de}	0.03 ± 0.01^{e}	35.75 ± 5.87^{c}	0.57 ± 0.14^{d}
ACS	3.67 ± 0.93^{e}	21.37 ± 4.38^{e}	0.39 ± 0.12^{c}	25.42 ± 4.40^{d}	0.46 ± 0.11^{e}
CD (p = 0.05)	1.05	4.03	0.05	4.11	0.11
Landscape position					
Lowland area	8.99 ± 3.35^{a}	31.89 ± 6.50^{a}	0.36 ± 0.23^{a}	41.24 ± 8.40^{a}	0.77 ± 0.20^{a}
Upland area	8.17 ± 2.87^{b}	26.49 ± 6.15^{b}	0.30 ± 0.21^{b}	34.96 ± 7.68^{b}	0.62 ± 0.17^{b}
CD (p = 0.05)	0.56	2.15	0.03	2.17	0.06

AHS Agri-horticulture system, *PO* Pure orchard, *TBP* Teak boundary plantations, *ACS* Annual cropping system, *CD* Critical difference, *SCD* Soil carbon density, *SOC* Soil organic carbon. The values carrying different alphabetical superscripts ($^{a,b,c,d,\ldots}$) within the columns above, differ significantly amongst themselves ($p < 0.05$)

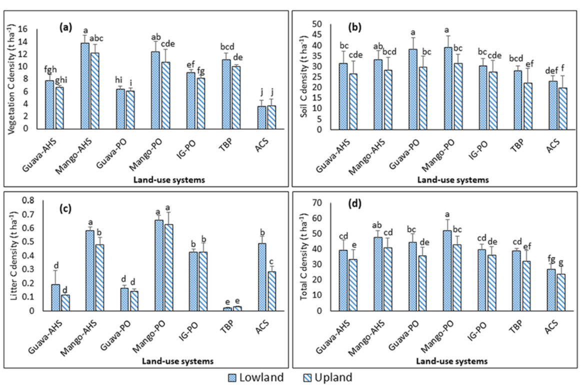


Fig. 3 Interaction effect of land use system and landscape position on the carbon storage. Here, (**a**) vegetation carbon density; (**b**) Soil carbon density; (**c**) litter carbon density; (**d**) total carbon density. AHS = Agri-horticulture system; PO = Pure orchard; TBP = Teak boundary plantations; IG = Indian gooseberry; ACS = Annual cropping system. The values carrying different alphabetical superscripts ($^{a,b,c,d,\ldots}$) above the bars, differ significantly amongst themselves ($p < 0.05$)

guava-PO. Similarly, in soil, a considerably ($p < 0.05$) higher C sequestration rate (1.78 t C ha^{-1} yr^{-1}), and CO_2 abatement potential (6.55 t CO_2 ha^{-1} yr^{-1}) were recorded in guava-PO system; statistically similar with mango-PO followed by guava-AHS, mango-AHS and IG-PO and lowest in TBP (0.31 t C ha^{-1} yr^{-1} and 1.15 t CO_2 ha^{-1} yr^{-1}). Moreover, the guava-PO exhibited the highest potential for the total C sequestration (1.16 t C ha^{-1} yr^{-1}), and CO_2 mitigation potential (7.76 t CO_2 ha^{-1} yr^{-1}). However, remained statistically identical to mango-PO, mango-AHS and guava-AHS were followed by IG-PO and had the lowest potential in TBP (0.86 t C ha^{-1} yr^{-1} and 3.16 t CO_2 ha^{-1} yr^{-1}). Apart from the various land use systems, the landscape position has a substantial ($p < 0.05$) influence on C sequestration, and CO_2 abatement potential in vegetation and total (including soil + vegetation), while having a non-significant influence in soil (Table 4). Remarkably, the lowland areas have a higher rate of vegetation (0.59 t C ha^{-1} yr^{-1}), and total C sequestration (1.68 t ha^{-1} yr^{-1}) compared to the upland areas. The CO_2 abatement potential also follows a similar trend with higher CO_2 mitigation potential in lowland areas. The interaction of land use systems × landscape position also significantly impacted the C sequestration rate and CO_2 abatement capacity. The considerably ($p < 0.05$) higher vegetation C sequestration rate (13.78 t C ha^{-1} yr^{-1}) and CO_2 abatement capacity (2.86 t CO_2 ha^{-1} yr^{-1}) were recorded under the mango-AFS × lowland areas. Conversely, the maximum soil and total C sequestration rate and CO_2 abatement potential were recorded under the guava-AHS × lowland areas (Fig. 4).

3.4 Carbon credits and economics

The potential of land use systems incorporating perennial components, specifically trees, was evaluated to determine their capacity for generating supplementary income via C credits. The results indicated that the guava-PO had provided significantly ($p < 0.05$) higher C credit (155.18 US$ ha^{-1} year^{-1}) (Table 5); however statistically ($p < 0.05$) identical to the mango-PO (129.76 US$ ha^{-1} year^{-1}), mango-AHS (115.86 US$ ha^{-1} year^{-1}) and

Table 4 Variation in rate of carbon sequestration and CO_2 mitigation potential among different land use system at two landscape position in semi-arid region of Vindhyan range

Treatments	C sequestration rate (t C ha^{-1} $year^{-1}$)			CO_2 mitigation potential		
	Vegetation	Soil	Total	Vegetation	Soil	Total
Land use systems						
Guava-AHS	0.50 ± 0.17^{cd}	1.09 ± 0.81^{b}	1.56 ± 0.90^{ab}	1.85 ± 0.63^{cd}	4.00 ± 2.98^{b}	5.72 ± 3.30^{ab}
Mango-AHS	0.78 ± 0.08^{a}	0.79 ± 0.39^{bc}	1.58 ± 0.42^{ab}	2.86 ± 0.30^{a}	2.89 ± 1.44^{bc}	5.79 ± 1.55^{ab}
Guava-PO	0.36 ± 0.08^{e}	1.78 ± 0.88^{a}	2.11 ± 0.90^{a}	1.33 ± 0.29^{e}	6.55 ± 3.24^{a}	7.76 ± 3.30^{a}
Mango-PO	0.59 ± 0.19^{b}	1.16 ± 0.51^{ab}	1.77 ± 0.59^{a}	2.17 ± 0.68^{b}	4.24 ± 1.86^{ab}	6.49 ± 2.18^{a}
Indian gooseberry-PO	0.41 ± 0.10^{de}	0.63 ± 0.17^{bc}	1.05 ± 0.16^{bc}	1.52 ± 0.36^{de}	2.31 ± 0.61^{bc}	3.84 ± 0.57^{bc}
TBP	0.58 ± 0.12^{bc}	0.31 ± 0.14^{c}	0.86 ± 0.22^{c}	2.12 ± 0.45^{bc}	1.15 ± 0.51^{c}	3.16 ± 0.80^{c}
CD ($p = 0.05$)	0.09	0.64	0.64	0.32	2.36	2.34
Landscape position						
Lowland area	0.59 ± 0.18^{a}	1.11 ± 0.88	1.68 ± 0.90^{a}	2.16 ± 0.67^{a}	4.06 ± 3.24	6.15 ± 3.31^{a}
Upland area	0.49 ± 0.17^{b}	0.82 ± 0.43	1.30 ± 0.38^{b}	1.78 ± 0.63^{b}	2.99 ± 1.60	4.77 ± 1.40^{b}
CD ($p = 0.05$)	0.05	NS	0.37	0.19	NS	1.35

AHS Agri-horticulture system, *PO* Pure orchard, *TBP* Teak boundary plantations, *ACS* Annual cropping system, *CD* Critical difference, *NS* Non-significant. The values carrying different alphabetical superscripts ($^{a,b,c,d,\ldots}$) within the columns above, differ significantly amongst themselves ($p < 0.05$)

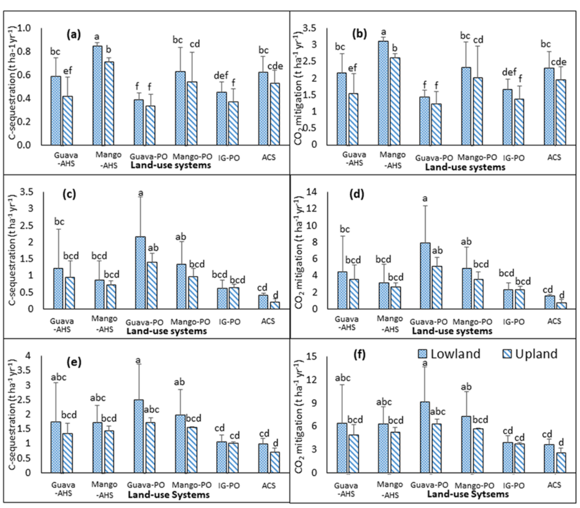


Fig. 4 Interaction effect of land use system and landscape position on the carbon sequestration and CO_2 mitigation potential. Here, (**a**) vegetation carbon sequestration; (**b**) vegetation CO_2 mitigation; (**c**) soil carbon sequestration; (**d**) soil CO_2 mitigation; (**e**) total carbon sequestration; (**f**) total CO_2 mitigation. AHS = Agri-horticulture system; PO = Pure orchard; IG = Indian gooseberry; TBP = Teak boundary plantations. The values carrying different alphabetical superscripts ($^{a,b,c,d,\ldots}$) above the bars, differ significantly amongst themselves ($p < 0.05$)

guava-AHS (114.48 US$ ha^{-1} $year^{-1}$) while TBP provided the lowest C credit (63.22 US$ ha^{-1} $year^{-1}$). The cost and return analysis revealed that significantly ($p < 0.05$) higher net returns were observed in the TBP (4984.86 US$ ha^{-1} $year^{-1}$) which was statistically at par with the mango-AHS (4835.48 US$ ha^{-1} $year^{-1}$); however, the maximum benefit–cost ratio was recorded under mango-AHS followed by mango-PO (5.21) and TBP (5.17) which was statistically at par with each other. The lowest net returns (800.23 US$ ha^{-1} $year^{-1}$), and benefit–cost ratio (1.23) was observed in the ACS. Moreover, if the amount of C credit is included in the net returns, it can provide additional monetary benefit to the farmers. In this scenario, the mango-PO still had the significantly highest benefit–cost ratio (6.01), with 2.39 per cent additional income. Similarly, the guava-PO recorded the maximum increment of 6.80 per cent while the minimum in the TBP (1.16%). Besides land use system, the landscape position also significantly influenced the C credit, with the lowland area having a higher potential to produce C credit (123.07 US$ ha^{-1} $year^{-1}$) than the upland area (95.37 US$ ha^{-1} $year^{-1}$). However, the landscape position did not significantly ($p > 0.05$) influence the economic parameters (Table 5).

4 Discussion

In the present day, estimating C content in global landscapes becomes crucial not only for determining global C cycle but also for playing a substantial role in efforts to mitigate climate change (Chavan et al. 2022). Similarly, in the current investigation, the different land use systems and landscape position significantly ($p < 0.05$) influence the biomass production, C sequestration and economic profitability.

Table 5 Variation in bio-economics among different land use systems at two landscape position in semi-arid region of Vindhyan range

Treatments	Bio-economics (US$ ha^{-1} $year^{-1}$)				Benefit cost ratio	Benefit cost ratio including carbon credit
	Cost of cultivation	Gross returns	Net returns	Carbon credit		
Land use systems (L)						
Guava-AHS	671.75	3585.53 ± 205.72[c]	2913.78 ± 205.72[c]	114.48 ± 66.03[ab]	4.34 ± 0.31[c]	4.51 ± 0.35[c]
Mango-AHS	823.39	5658.87 ± 382.43[a]	4835.48 ± 382.43[a]	115.86 ± 30.92[ab]	5.87 ± 0.46[a]	6.01 ± 0.49[a]
Guava-PO	653.11	2857.50 ± 163.92[d]	2204.39 ± 163.92[d]	155.18 ± 66.04[a]	3.38 ± 0.25[d]	3.61 ± 0.27[d]
Mango-PO	731.40	4543.19 ± 328.07[b]	3811.79 ± 328.07[b]	129.76 ± 43.61[a]	5.21 ± 0.45[b]	5.40 ± 0.48[b]
Indian gooseberry-PO	593.47	3057.69 ± 172.54[d]	2464.22 ± 172.54[d]	76.84 ± 11.41[bc]	4.15 ± 0.29[c]	4.28 ± 0.28[c]
TBP	964.69	5949.56 ± 440.78[a]	4984.86 ± 440.78[a]	63.22 ± 16.00[c]	5.17 ± 0.46[b]	5.23 ± 0.46[b]
ACS	652.10	1452.33 ± 147.62[e]	800.23 ± 147.62[e]	-	1.23 ± 0.23[e]	1.23 ± 0.23[e]
CD ($p = 0.05$)	-	312.56	312.56	46.84	0.39	0.40
Landscape position (A)						
Lowland area	727.13	3892.00 ± 1565.14	3128.44 ± 1465.44	123.07 ± 66.11[a]	4.17 ± 1.51	4.31 ± 1.56
Upland area	727.13	3902.68 ± 1539.04	3161.49 ± 1438.84	95.37 ± 27.91[b]	4.22 ± 1.49	4.33 ± 1.52
CD ($p = 0.05$)	-	NS	NS	27.04	NS	NS

AHS Agri-horticulture system, *PO* Pure orchard, *TBP* Teak boundary plantations, *ACS* Annual cropping system, *CD* Critical difference, *NS* Non-significant. The values carrying different alphabetical superscripts ([a,b,c,d,…]) within the columns above, differ significantly amongst themselves ($p < 0.05$)

4.1 Biomass accumulation

The potential for biomass production in vegetation is influenced by various driving factors, viz., tree species, productive capacity of the site, quality of the planting material, agronomic management practices and density (Newaj et al. 2016; Yadav et al. 2019). In the current study, enhanced biomass accumulation in mango-based systems (mango-AHS followed by mango-PO) could be ascribed to the inherent characteristics of trees (large tree crown and evergreen nature), uninhibited growth and unmanaged canopies (no training and pruning). Concurrently, the mango trees exhibit greater age and larger size due to their genetic composition, resulting in a more significant biomass accumulation than guava-based systems (such as AHS and PO), since the pace at which a tree accumulates biomass is influenced by both its size and age, consistent with metabolic scaling theory. This theory suggests that tree mass development rate should exhibit a constant rise in conjunction with tree age and size (Cyamweshi et al. 2021; Enquist et al. 1999). Therefore, in the current investigation, the subsequent trend was as followed: Mango-based systems (age 12 years) > TBP (12 years) > IG-PO (12 years) > guava-based systems (7 years) > ACS. The discrepancy in accumulation between mango-based systems and TBP may be attributed to the disparity in system density.

The higher biomass accumulation observed in TBP, in contrast to IG systems, can be attributed to the superior growth rate exhibited by teak trees compared to IG (Newaj et al. 2016). Our results are consistent with other studies carried out in the different parts of India, which reveal that 12-years-old mango-based AFS had a biomass production potential of 55.1 t ha^{-1} in the Indian sub-Himalayas (Rathore et al. 2021), whereas, 2–10 years-old guava-PO systems (275 tree ha^{-1}) under hot and sub-humid climate had a lower biomass production potential (0.54–9.26 t ha^{-1}) (Naik et al. 2021). In semi-arid part of the Vindhyan region, the agriculture systems were found to have biomass accumulation of 9.39–12.24 t ha^{-1}, followed by guava-AHS (21.68 t ha^{-1}) and teak based forest (75.82 t ha^{-1}) (Roy et al. 2022). According to Toppo et al. (2021), the teak based AFS in humid subtropical climate have a potential to accumulate biomass in the range of 21.62–29.14 t ha^{-1} $year^{-1}$. Newaj et al. (2016) observed that 15 years-old IG-based AFS with 100 trees ha^{-1} in Central India (semi-arid region) exhibited a biomass production of 14.99 t ha^{-1}. Similarly, Wankhede et al. (2018), also found that 12–14 years-old IG-PO having a density of 173–300 trees ha^{-1} in a semi-arid region has a biomass production potential ranging from 13.96–24.18 t ha^{-1} in comparison to 17.25 t ha^{-1} found in current study. On the contrary, in 8 year old IG based AFS of north western Himalayas, Bhatia et al. (2022) reported comparatively higher biomass was reported (62.60–73.71 t ha^{-1}) compared to total biomass of IG-PO in present investigation.

Furthermore, higher accumulation of biomass in the AFS, particularly the mango-AHS, compared to the mango-PO, may be attributed to the synergetic influence of the various components in the AFS. Nevertheless, the PO systems (guava and mango) exhibit a relatively higher density when compared to the AHS; thus, the trees grown in AFS have better space for growth and development.

Simultaneously, the interstitial spaces among the rows of trees were effectively utilized to cultivate the agricultural crops, leading to better resource exploitation and significantly contributing to biomass buildup (Rajput et al. 2015, 2017). Contrary to present investigation, Swamy and Puri (2005) reported that the *Gmelina arborea* based plantation ecosystem (21.7 t ha^{-1}) has higher total biomass accumulation potential compared to *Gmelina arborea*-based agrisilviculture systems (14.1 t ha^{-1}) in Central India, owing to lower growth and development in the AFS due to competition. Simultaneously, the maximum BGB in the mango-AHS attributed to the presence of large-sized trees in AF was associated with a more extensive tap root and lateral root system, which leads to a more significant amount of BGB and, subsequently, enhanced input of SOC obtained from the roots (Zhuang et al. 2015).

Moreover, litter has a crucial role in conversion of organic matter from plants to soil and release of nutrients throughout the litter decomposition process (Bhardwaj et al. 2023) beside a driving force that influences macrofaunal populations. In the current investigation, there was marked variation in the litter biomass production among the different systems, with mango-based systems having higher litter biomass production than other systems, mainly owing to the larger canopy of the mango trees leading to higher litter fall and comparably lower rate of litter decomposition. Notably, the litter biomass is contingent upon the amount of litter that falls, and litterfall production has been seen to exhibit temporal and spatial fluctuations, which are controlled by tree growth and various natural and anthropogenic factors (Verma et al. 2022). Previous studies showed that the litter fall produced annually in 11-year-old teak plantation (Jha 2010) and 12-year-old mango orchard (6 × 3 m) amounted to 5.7 t ha^{-1} and 3.52–7.61 t ha^{-1} (Murovhi et al. 2012), respectively, however, Ganeshamurthy et al. (2019) indicated that the mango orchards in India have litter biomass production of about 1.42 t ha^{-1} which is similar to the finding of current investigation. Aside from differing land use regimes, landscape position substantially impacts biomass production. Higher biomass output in lowland regions was primarily attributable to superior growing circumstances, including improved soil fertility and organic matter (Sharma et al. 2022).

4.2 Carbon density and sequestration

The C storage potential in the different agro-ecosystems is closely related to the quantity of biomass in various components in vegetation. However, C density and sequestration capacity of AF was subject to variation based on factors such as meteorological conditions (mainly the variation in the lowland and upland landscape position in the current investigation), tree age and management within the landscape (Marone et al. 2017; Montagnini and Nair 2004), historical land use, site quality and tree species (Dhyani et al. 2016). In the current study, the mango-AHS had higher vegetation C density while the mango-PO had maximum total C density mainly attributed to tree density, morphological traits and productivity of the agricultural crops. Since, Kuyah et al. (2014) also demonstrate that the choice of tree species significantly influences C storage, as it imposes a constraint on the upper limit of C sequestration achievable under favorable circumstances. Moreover, the incorporation of trees and shrubs within an agro-ecosystem frequently results in favorable conditions and higher productivity of AFS (Garima et al. 2021; Verma et al. 2023a, 2023b), hence presenting prospects for the augmentation of C sequestration (Albrecht and Kandji 2003). Several studies have reported similar findings, indicating that larger trees possess an enhanced capacity to sequester C than smaller trees (Sheil et al. 2017; Stephenson et al. 2014). Moreover, the lowest C density was recorded under ACS owing to two facts (i) after crop harvest whole biomass will be transported out of the system and (ii) the farmland remains devoid of crops signifying a prolonged period during which no biomass accumulation occurred in that area (Roy et al. 2022). Additionally, these outcomes closely align with previous findings of Sarangle et al. (2018), Rajput et al. (2015, 2017) and Yadav et al. (2015).

Furthermore, mango-PO were shown to have greater SCD in the current study, owing to increased litter and SOC and lower bulk density (Table S1; Fig. S1) compared to other systems. In a previous study conducted by Gupta and Sharma (2013), it was observed that the mango-PO had a greater SCD (50.70 t ha^{-1}), in comparison to the guava-PO (40.21 t ha^{-1}), which aligns with the findings of current investigation. On the contrary, in Southern Gujarat region, Parmar et al. (2021) observed relatively higher vegetation C density (35.76 t ha^{-1}) in mango-AFS compared to values recorded (13.01 t ha^{-1}) in the present investigation. In the current study, the mango-PO system exhibited higher litter C density due to higher litter fall. However, variations in the C density of the soil surface layer among ecosystems can be attributed to disparities in the amount and quality of fallen leaves, the C content within the litter, and the processes of disintegration and degradation (Gera et al. 2011). Interestingly, the ACS has a significantly lower litter C density comparable to other systems being evaluated, except for TBP, which have the lowest litter C density. The observed phenomenon of low litter C density in the TBP may be explained by several factors, including the practice of heavy pruning in teak trees to achieve a clear bole, farmer practice of burning of teak leaves (due to larger size) and increased likelihood of leaves being carried away by air currents.

The rate at which plants generate biomass has a direct impact on their capacity to effectively mitigate atmospheric CO_2 levels. A greater biomass in tree components leads to increased CO_2 absorption and sequestration potential. The C sequestration rate also exhibited notable variations in both soil and vegetation, aligning with prior research findings. Specifically, the mango-AHS and guava-PO have the highest C sequestration and abatement capacity in vegetation and soil, respectively. Particularly, the level of C sequestration in the soil is substantial when a sufficient amount of litterfall is attributed to it on a yearly basis (Oelbermann and Voroney 2007). Nevertheless, the observed variations can be ascribed to the random deposition of leaf-litter as well as root turnover during the course of many years. However, the guava systems have the highest total C sequestration, CO_2 abatement and C credit generation potential, followed by mango-based systems. Conversely, Shinde et al. (2015) observed that mango trees exhibit more biomass production and possess a better capacity for C storage and sequestration when compared to guava trees. According to Ganeshamurthy et al. (2019), mango-PO have a mean litter C density of 0.645 t ha^{-1} and a SCD of 53.68 t ha^{-1}, with a total C density ranging from 91.20 to 177.65 t ha^{-1}. The litter C density was comparable to the current analysis; however, the SCD and TCD were on the upper side compared to the current investigation. In their study, Wankhede et al. (2018) in an IG-PO located in a semi-arid environment observed a range of SCD values between 8.96 and 12.78 t ha^{-1}, with a TCD varying from 19.17–24.87 t ha^{-1}. Newaj et al. (2016) indicated that the IG-based AFS in semi-arid region of the country had C storage potential of 7.12 t C ha^{-1} with C sequestration potential of 0.47 t C ha^{-1} yr^{-1}. Kaul et al. (2010) found that the teak trees exhibit 2 t C ha^{-1} yr^{-1} rate of C sequestration rate, which is on a higher side than the present study. Numerous other scientific studies have indicated that the C sequestration potential of AF practices in India ranges from 0.29 to 15.21 Mg C ha^{-1} year^{-1} (Chavan et al. 2021).

5 Carbon credits and economics

Aside from biomass accumulation and C storage done by tree-based systems, economic feasibility also plays a substantial role in determining adoption of specific land use systems within the region. In the current investigation, mango-AHS exhibited the maximum returns and benefit–cost ratio owing to the higher returns from the fruit crop and subsequent benefits from the agricultural crops. Likewise, Rathore et al. (2013) observed that the mango-based AFS was shown to have more monetary advantages due to the mango trees' sparse foliage, that allowed intercropping, leading to enhanced yields, especially in rainfed areas of the Western Himalaya. However, ACS provides the lowest returns owing to the dependency on only one component, i.e., agriculture crops. Previous studies (Chandana et al. 2020; Garima et al. 2021) have argued that the AFS has more economic feasibility due to the synergetic influence of different components on each other compared to the monocropping system.

Furthermore, the economic viability of C credits in relation to CO_2 mitigation has demonstrated a notable and anticipated positive impact, therefore warranting their recognition as supplementary sources of revenue. Nevertheless, the economic influence of C credit was rather little (1.16–6.80%) while looking at systems' overall economic performance, besides the fact that we have not considered the cost associated with monitoring, reporting and verification procedure. In this regard, C revenue as a financial justification for changing current land use would be unappealing. Similar to the finding of the current investigation, Goncalves et al. (2021) observed that coffee AFS exhibit substantial C sequestration; however, despite this positive aspect, the economic impact of C sequestration does not sufficiently incentivize the adoption of these systems primarily attributed to the low revenue generated from C credits. Similarly, Roy et al. (2022) demonstrated that the different land use systems including agriculture, AFS and teak based forest system of semi-arid region of Vindhyan ranges have C credit generation potential of 689 to 5565 US$ ha^{-1}. Conversely, Waldén et al. 2020) demonstrated that introducing C revenue can enhance the profitability of specific Ethiopian AFS by as much as 70%.

6 Conclusion

In an epoch characterized by a compelling need to balance human growth and environmental preservation, the nexus of C storage and economic efficiency within fruit-based AFS plays a critical role. Since fruit-based systems have the potential for establishing mutually beneficial relationships among adaptation and mitigation efforts while sustaining the livelihood of the farmers. The current study concludes that in semi-arid region, pure orchard and AFS particularly guava and mango systems played a key role, offering a unique combination of carbon sequestration, CO_2 mitigation, and the generation of carbon credits. Thus, recognizing and promoting the distinct advantages of this system could significantly enhance both environmental and economic outcomes. Additionally, the findings emphasize the need for nuanced policy approaches that acknowledge the role of different agroforestry systems, as mango-AHS not only in biomass accumulation but also in providing substantial monetary benefits underscores the importance of recognizing and harnessing the specific strengths of each system. Nevertheless, it is imperative to acknowledge that the contribution of carbon credits to the overall system income was less than 7%, underscoring their limited role as a driver for economic growth in these specific land use systems. In light of the findings, the study advocates for a strategic policy focus on promoting agri-horticulture systems or at least pure orchard systems. Since, beyond their evident environmental benefits such as biomass production and carbon storage, these systems demonstrate a consistent capacity to deliver higher annual returns, presenting a holistic and economically viable approach that aligns with sustainable agricultural practices.

Abbreviations

ACS	Annual cropping system
AF	Agroforestry
AFS	Agroforestry systems
AGB	Above ground biomass
AHS	Agri-horticulture system
BGB	Below ground biomass
C	Carbon
CD	Critical difference
CO_2	Carbon dioxide
dbh	Diameter at breast height
eq	Equivalent
IG	Indian gooseberry
PO	Pure orchard
$REDD^+$	Reducing emissions from deforestation and forest degradation
SCD	Soil carbon density
SOC	Soil organic carbon
TBP	Teak boundary plantation
TCD	Total carbon density
UN	United nations

Supplementary Information

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Additional file 1: Table S1. Effect of land use system and landscape position on bulk density and soil carbon density at different depths. **Figure S1.** Interaction effect of (a) land use system and landscape position on the soil organic carbon (b) land use system and soil depth on the soil organic carbon.

Additional file 2. Statistical analysis of observed datasets indicating degree of freedom and F calculated value and *p*-value.

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Authors' contributions
All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Manoj Kumar Singh, Sarvan Yadav, Bhalendra Singh Rajput and Prashant Sharma. The first draft of the manuscript was written by Prashant Sharma and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

Competing interests
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References

Adhikari B, Lodhiyal N, Lodhiyal L (2020) Assessment of crop yield, productivity and carbon sequestration in agroforestry systems in Central Himalaya, India. Agrofor Syst 94:281–296
Albrecht A, Kandji ST (2003) Carbon sequestration in tropical agroforestry systems. Agr Ecosyst Environ 99:15–27
Baah-Acheamfour M, Carlyle CN, Lim S-S, Bork EW, Chang SX (2016) Forest and grassland cover types reduce net greenhouse gas emissions from agricultural soils. Sci Total Environ 571:1115–1127
Bhardwaj D, Tahiry H, Sharma P, Pala NA, Kumar D, Kumar A (2021) Influence of aspect and elevational gradient on vegetation pattern, tree characteristics and ecosystem carbon density in Northwestern Himalayas. Land 10:1109
Bhardwaj DR, Sharma P, Kumar D, Panwar P, Kumar A, Pala NA, Rajput BS, Kumar R, Negi V, Rajput P, Salve A, Chisanga K, Tahiry H (2023) Chapter 13 - Carbon stock inventory and biomass production in different land use systems of Northwestern Himalaya. In: Jong WD, Kumar M, Pandey R (eds) Kumar A. Climate Change in the Himalayas, Academic Press, pp 217–233
Bhatia AK, Sharma K, Pant K, Singh S, Prakash P, Kumar P, Sharma H (2022) Economic profitability and carbon stock potential of cereals and pulses under harar and aonla based agroforestry systems in the low hill zone of Himachal Pradesh. Int J Econ Plants 9:170–173
Bitlerlich W (1984) The relaskop idea slough: Commonwealth agricultural bureause. Farnham Royal, England
Blake GR, Hartge KH (1986) Methods of soil analysis. American Society of Agronomy. Inc., Publisher, Madison, USA
Brown S (1997) Estimating biomass and biomass change of tropical forests: a primer. Food and Agriculture Organization of the United Nations, Rome
Chandana P, Lata AM, Khan MA, Krishna A (2020) Climate change smart option and doubling farmer's income through Melia dubia-based agri-silviculture system. Curr Sci 118:444
Chauhan SK, Sharma S, Chauhan R, Naveen G (2010) Accounting poplar and wheat productivity for carbon sequestration in agri-silvicultural system. Ind Forester 136:1174–1182
Chavan S, Dhillon R, Ajit, Rizvi R, Sirohi C, Handa A, Bharadwaj K, Johar V, Kumar T, Singh P (2022) Estimating biomass production and carbon sequestration of poplar-based agroforestry systems in India. Environ Dev Sustain 24:13493–13521
Chavan S, Newaj R, Rizvi R, Ajit PR, Alam B, Handa A, Dhyani S, Jain A, Tripathi D (2021) Reduction of global warming potential vis-à-vis greenhouse gases through traditional agroforestry systems in Rajasthan, India. Environ Dev Sustain 23:4573–4593
Chavan SB, Dhillon RS, Sirohi C, Uthappa AR, Jinger D, Jatav HS, Chichaghare AR, Kakade V, Paramesh V, Kumari S (2023) Carbon sequestration potential

of commercial Agroforestry systems in Indo-Gangetic plains of India: poplar and eucalyptus-based Agroforestry systems. Forests 14:559
Cubasch U, Wuebbles D, Chen D, Facchini MC, Frame D, Mahowald N, Winther JG (2013) Introduction. In: Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate Change 2013: The physical science basis contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change, Cambridge University Press. Cambridge University Press, Cambridge, United Kingdom
Cyamweshi AR, Kuyah S, Mukuralinda A, Muthuri CW (2021) Potential of Alnus acuminata based agroforestry for carbon sequestration and other ecosystem services in Rwanda. Agrofor Syst 95:1125–1135
Das P, Dhara PK, Panda S (2022) Fruit based agroforestry systems-potential means for sustaining carbon sequestration, improving soil health and diet of community in red and lateritic zone of West Bengal, India. Int J Sci Eng Res 13:832–843
Dhyan S, Ram A, Dev I (2016) Potential of agroforestry systems in carbon sequestration in India. Dhyani, SK, Ram, a, Dev I:1103–1112
Dhyani S, Ram A, Dev I (2016) Potential of agroforestry systems in carbon sequestration in India. Ind J Agri Sci 86:1103–1112
Enquist BJ, West GB, Charnov EL, Brown JH (1999) Allometric scaling of production and life-history variation in vascular plants. Nature 401:907–911
Ganeshamurthy AN, Kalaivanan D, Rajendiran S (2020) Carbon Sequestration Potential of Perennial Horticultural Crops in Indian Tropics. In: Ghosh P, Mahanta S, Mandal D, Mandal B, Ramakrishnan S (eds) Carbon Management in Tropical and Sub-Tropical Terrestrial Systems. Springer, Singapore, p 333–348
Ganeshamurthy A, Ravindra V, Rupa T (2019) Carbon sequestration potential of mango orchards in India. Curr Sci 117:2006–2013
Garima BD, Thakur C, Kaushal R, Sharma P, Kumar D, Kumari Y (2021) Bamboo-based agroforestry system effects on soil fertility: Ginger performance in the bamboo subcanopy in the Himalayas (India). Agron J 113:2832–2845
Gera M, Giresh M, Bisht N, Gera N (2011) Carbon sequestration potential of agroforestry under CDM in Punjab State of India. Indian J for 34:1–10
Gomez KA, Gomez AA (1984) Statistical procedures for agricultural research. John wiley & sons, New York
Goncalves N, Andrade D, Batista A, Cullen L, Souza A, Gomes H, Uezu A (2021) Potential economic impact of carbon sequestration in coffee agroforestry systems. Agrofor Syst 95:419–430
Goswami S, Verma KS, Pala NA (2016) Impact of input use on biomass attributes and carbon mitigation in agroforestry systems of Indian Himalaya. Ind Forester 142:1214–1219
Gupta M, Sharma S (2013) Status of sequestered organic carbon in the soils under different orchards in Uttarakhand State. Ind Horticult J 3:6–9
IPCC (2019) IPCC Special report on climate change, desertifcation, land degradation, sustainable land management, food security, and greenhouse gas fuxes in terrestrial ecosystems. Intergovernmental Panel on Climate Change, London, UK
Jha K (2010) Litter production and leaf litter decomposition dynamics in an age series Tectona grandis Linn. f. plantations of moist Tarai Sal forest. Ind Forester 136:433–450
Jose S, Bardhan S (2012) Agroforestry for biomass production and carbon sequestration: an overview. Agrofor Syst 86:105–111
Kumara K, Pal S, Chand P, Kandpal A (2023) Carbon sequestration potential of agroforestry systems in Indian agricultural landscape: a meta-analysis. Ecosyst Serv 62:101537
Kuyah S, Sileshi GW, Njoloma J, Mng'omba S, Neufeldt H (2014) Estimating aboveground tree biomass in three different miombo woodlands and associated land use systems in Malawi. Biomass Bioenerg 66:214–222
Kaul M, Mohren GMJ, Dadhwal VK (2010) Carbon storage and sequestration potential of selected tree species in India. Mitig Adapt Strateg Glob Chang 15: 489–510
Lal R (2004) Soil carbon sequestration to mitigate climate change. Geoderma 123:1–22
Marone D, Poirier V, Coyea M, Olivier A, Munson AD (2017) Carbon storage in agroforestry systems in the semi-arid zone of Niayes, Senegal. Agrofor Syst 91:941–954
Mokany K, Raison RJ, Prokushkin AS (2006) Critical analysis of root: shoot ratios in terrestrial biomes. Glob Change Biol 12:84–96
Montagnini F, Nair PR (2004) Carbon sequestration: an underexploited environmental benefit of agroforestry systems. Agrofor Syst 61:2841–295
Murovhi NR, Materechera SA, Mulugeta SD (2012) Seasonal changes in litter fall and its quality from three sub-tropical fruit tree species at Nelspruit, South Africa. Agrofor Syst 86:61–71
Naik SK, Sarkar PK, Das B, Singh AK, Bhatt BP (2021) Biomass production and carbon stock in Psidium guajava orchards under hot and sub-humid climate
Nelson DW, Sommers LE (1996) Total carbon, organic carbon and organic matter. In: Sparks DL, Page AL, Helmke PA, Loeppert RH, Soltanpour PN, Tabatabai MA, Johnston CT, Summer ME (eds) Method of Soil Analysis Part 3 Chemical Methods. Soil Science Society of America, Madison, WI, USA, pp 961–1010
Newaj R, Chavan S, Alam B, Dhyani S (2016) Biomass and carbon storage in trees grown under different agroforestry systems in semi arid region of central India. Ind Forester 142:642–648
Oelbermann M, Voroney RP (2007) Carbon and nitrogen in a temperate agroforestry system: using stable isotopes as a tool to understand soil dynamics. Ecol Engine 29:342–349
Panwar P, Mahalingappa DG, Kaushal R, Bhardwaj DR, Chakravarty S, Shukla G, Thakur NS, Chavan SB, Pal S, Nayak BG (2022) Biomass production and carbon sequestration potential of different agroforestry systems in India: a critical review. Forests 13:1274
Parmar M, Arunachalam A, Jha S, Tandel M, Patel D, Bahera L (2021) Estimation of carbon sequestration potential of horticulture-based agroforestry systems in South Gujarat. Ind J Agroforestry 23:99–106
Pearson TR, Brown SL, Birdsey RA (2007) Measurement guidelines for the sequestration of forest carbon. US Department of Agriculture Forest Service, Pennsylvania
Penman J, Gytarsky M, Hiraishi T, Krug T, Kruger D, Pipatti R, Buendia L, Miwa K, Ngara T, Tanabe K (2003) Good practice guidance for land use, land-use change and forestry. Intergovernmental Panel on Climate Change, Japan
Pressler M (1895) Das Gesetz der Stambildung Leipzig. 153
Rajput BS, Bhardwaj D, Pala NA (2015) Carbon dioxide mitigation potential and carbon density of different land use systems along an altitudinal gradient in north-western Himalayas. Agrofor Syst 89:525–536
Rajput BS, Bhardwaj D, Pala NA (2017) Factors influencing biomass and carbon storage potential of different land use systems along an elevational gradient in temperate Northwestern Himalaya. Agrofor Syst 91:479–486
Rathore AC, Mehta H, Islam S, Saroj P, Sharma N, Jayaprakash J, Gupta A, Dubey R, Ghosh B, Prasad R (2021) Biomass, carbon stocks estimation and predictive modeling in mango based land uses on degraded lands in Indian Sub-Himalayas. Agrofor Syst 95:1563–1575
Rathore AC, Saroj P, Lal H, Sharma N, Jayaprakash J, Chaturvedi O, Raizada A, Tomar J, Dogra P (2013) Performance of mango based agri-horticultural models under rainfed situation of Western Himalaya, India. Agrofor Syst 87:1389–1404
Reppin S, Kuyah S, de Neergaard A, Oelofse M, Rosenstock TS (2020) Contribution of agroforestry to climate change mitigation and livelihoods in Western Kenya. Agrofor Syst 94:203–220
Rogelj J, Meinshausen M, Schaeffer M, Knutti R, Riahi K (2015) Impact of short-lived non-CO2 mitigation on carbon budgets for stabilizing global warming. Environ Res Lett 10:075001
Roy O, Meena RS, Kumar S, Jhariya MK, Pradhan G (2022) Assessment of land use systems for CO2 sequestration, carbon credit potential, and income security in Vindhyan region, India. Land Degrad Dev 33:670–682
Sarangle S, Rajasekaran A, Benbi D, Chauhan S (2018) Biomass and carbon stock, carbon sequestration potential under selected land use systems in Punjab. For Res Engine: Int J 9:75–80
Sharma P, Bhardwaj DR, Singh MK, Nigam R, Pala NA, Kumar A, Verma K, Kumar D, Thakur P (2023) Geospatial technology in agroforestry: status, prospects, and constraints. Environ Sci Pollut Res Int 30:116459–116487
Sharma P, Singh M, Verma K, Prasad SK (2022) Soil weed seedbank under different cropping systems of middle Indo-gangetic plains. Plant Soil Environ 68:542–551
Sheil D, Eastaugh CS, Vlam M, Zuidema PA, Groenendijk P, van der Sleen P, Jay A, Vanclay J (2017) Does biomass growth increase in the largest trees? Flaws, fallacies and alternative analyses. Funct Ecol 31:568–581

Shinde S, Turkhade P, Deshmukh S, Narkhede G (2015) Carbon sequestration potential of some fruit trees in Satara district of Maharashtra India. Ecol Environ Conserv Paper 21:359–362
Smith DM (1954) Maximum moisture content method for determining specific gravity of small wood samples. United States Department of Agriculture Forest Service, Forest Products Laboratory, Wisonsin
Solomon S, Qin D, Manning M, Averyt K, Marquis M (2007) Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC. Cambridge University Press, Cambridge
Stephenson NL, Das AJ, Condit R, Russo SE, Baker PJ, Beckman NG, Coomes DA, Lines ER, Morris WK, Ruger N, Alvarez E, Blundo C, Bunyavejchewin S, Chuyong G, Davies SJ, Duque A, Ewango CN, Flores O, Franklin JF, Grau HR, Hao Z, Harmon ME, Hubbell SP, Kenfack D, Lin Y, Makana JR, Malizia A, Malizia LR, Pabst RJ, Pongpattananurak N, Su SH, Sun IF, Tan S, Thomas D, van Mantgem PJ, Wang X, Wiser SK, Zavala MA (2014) Rate of tree carbon accumulation increases continuously with tree size. Nature 507:90–93
Swamy S, Puri S (2005) Biomass production and C-sequestration of Gmelina arborea in plantation and agroforestry system in India. Agrofor Syst 64:181–195
Toppo P, Oraon P, Singh BK, Kumar A (2021) Biomass, productivity and carbon sequestration of Tectona grandis and Gmelina arborea-based silvipastoral system. Curr Sci 121:1594
UN (2015) World Population Prospects: The 2015 Revision, key findings, and advance tables. United Nations Department of Economic and Social Affairs, New York
Verma A, Kumar P, Soni M, Pawar N, Pradhan U, Tanwar S, Kumar S (2022) Litter production and litter dynamics in different agroforestry systems in the arid western region of India. Biol Agric Hortic 38:40–60
Verma K, Prasad S, Singh M, Sharma P (2023a) Response of alley-cropped pearl millet (Pennisetum glaucum) to nitrogen and zinc schedules under semi-arid regions. Ind J Agronomy 68:105–109
Verma K, Prasad SK, Singh MK, Sharma P (2023b) Assessment of agronomic zinc biofortification of alley cropped Pearl Millet. Bangladesh J Bot 52:203–209
Verma T, Bhardwaj DR, Sharma U, Sharma P, Kumar D, Kumar A, Kumar A (2023c) Agroforestry systems in the mid-hills of the north-western Himalaya: a sustainable pathway to improved soil health and climate resilience. J Environ Manage 348:119264
Waldén P, Ollikainen M, Kahiluoto H (2020) Carbon revenue in the profitability of agroforestry relative to monocultures. Agrofor Syst 94:15–28
Walkley A, Black IA (1934) An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci 37:29–38
Wankhede S, Saini MK, Kothari S, Bala N, Singh G, Gour VS (2018) Evaluation of carbon sequestration potential in Amla (Emblica officinalis Gaertn.) Orchards in semi-arid region of India. Proc Natl Acad Sci, Ind Sect B: Biol Sci 88:1655–1660
Watson RT, Noble IR, Bolin B, Ravindranath N, Verardo DJ, Dokken DJ (2000) Land use, land-use change and forestry: a special report of the Intergovernmental Panel on Climate Change. Cambridge University Press
Woomer PL (1993) The impact of cultivation on carbon fluxes in woody savannas of Southern Africa. Water Air Soil Pollut 70:403–412
Yadav R, Bisht JK, Pandey BM (2015) Above ground biomass and carbon stock of fruit tree based land use systems in Indian Himalaya. Ecoscan 9:779–783
Yadav R, Gupta B, Bhutia P, Bisht J, Pattanayak A (2019) Sustainable agroforestry systems and their structural components as livelihood options along elevation gradient in central Himalaya. Biol Agric Hortic 35:73–95
Zahoor S, Dutt V, Mughal A, Pala NA, Qaisar K, Khan P (2021) Apple-based agroforestry systems for biomass production and carbon sequestration: implication for food security and climate change contemplates in temperate region of Northern Himalaya, India. Agrofor Syst 95:367–382
Zhuang S, Ji H, Zhang H, Sun B (2015) Carbon storage estimation of Moso bamboo (Phyllostachys pubescens) forest stands in Fujian, China. Trop Ecol 56:383–391

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