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RESEARCH ARTICLE

Eco-investments: Quantification of carbon sequestration potential and economic valuation of multifunctional agroforestry system

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Abstract

The study was carried out to quantify the carbon stock and sequestration potential of the multifunctional agroforestry (MFA) system established for small and marginal farmers in Tamil Nadu, India. The MFA consists of 316 multi-utility trees and shrubs across four quadrats and border trees on a 0.75 acre land. The results showed significant variation in the above-ground and below-ground carbon stock among the different tree and shrub species. *Neolamarckia cadamba* recorded the highest above and below-ground stock of 70.65 kg tree^{-1} and 18.37 kg tree^{-1}, respectively. The total carbon sequestered by the vegetation was 3.82 tons (3823.94 kg), with the highest contribution from Quadrat II (1591.85 kg) and the lowest from border trees (132.30 kg). The soil organic carbon (SOC) stock decreased with increasing depth, with the maximum stock observed in the 0-20 cm layer. The total change in SOC stock from the MFA during the study period was 12.99 mg ha^{-1}, with a carbon sequestration rate of 0.18 mg ha^{-1} yr^{-1}. The total carbon revenue from the vegetation and soil was estimated at US$ 311.4 (US$ 140.3 from vegetation and US$ 171.1 from soil). The findings highlight the significant potential of MFA systems in carbon sequestration and mitigation of climate change, particularly for small and marginal farmers in developing countries.

Keywords

carbon revenue; carbon sequestration; carbon stock; climate change; multifunctional agroforestry (MFA) system; soil organic carbon

Introduction

Climate change and global warming have become significant global issues affecting the sustainability of agroecosystems, particularly with negative effects on farm productivity (1). Global air temperatures have increased by 1.53°C from the pre-industrial era and are expected to increase by 1.4–5.8°C by the year 2100 (2). Concurrently, the world's population is also expected to grow at a rapid rate and reach 9.7 billion people by 2050, which is 34% more than it is now (3), posing an impact on people's access to food and means of subsistence. More than 70% of people in India depend on agriculture for a living, with small and medium-sized marginal landholders making up the majority. They are particularly sensitive to the effects of climate change in this country (4).

In light of the aforementioned context, it is essential to adopt nature-based farming methods, with a focus on agroforestry systems (AFS), which include perennial trees on farmlands. Agroforestry has the capacity to accumulate enormous amounts of carbon for extended periods of time, which makes it a useful tool for reducing and adapting to the negative impacts of climate change in line with the Kyoto Protocol and several international agreements (5). In a previous study, the potential for sequestering carbon in several agroforestry systems was estimated, with the biomass and carbon stock varying in the following order: Horti-silvi-pasture (66.55 and 25.07 t ha^{-1}) > agri-horti-silviculture (50.18 and 38.82 t ha^{-1}) > horti-agriculture (36.22 and 5.63 t ha^{-1}) > agri-silviculture (34.87 and 8.68 t ha^{-1}) (6). More than 20% of the global population depends on the many ecosystem services provided by AFS, particularly in developing countries possessing a carbon abatement potential of around 1.1–2.2 Pg C (7). India enacted the National Agroforestry Policy 2014 in recognition of the critical role that agroforestry plays with the specific goal of accelerating the use of agroforestry techniques. Furthermore, as part of its nationally defined commitment to the Paris Climate Agreement, the Indian government has committed to sequestering an additional 2.5–3.0×10^9 tCO_2e by the year 2030. This is made feasible by promoting the growth of multipurpose trees on farmlands (5).

Despite not being intended for carbon sequestration, several national and international organizations have recognized agroforestry's significant contribution to soil and vegetation-based carbon sequestration. Reorienting farming practices, such as creating MFA landscapes, has become imperative due to the impact of climate change, offering various benefits, including increased productivity, carbon storage, livelihood security and revenue for small farmers (8). In addition, little research has been done on the role of small-scale agroforestry in the storage of carbon and lowering of global emissions (9). Insufficient data to bolster the incorporation and advancement of small-scale agroforestry in climate change discussions may mislead policymakers (10). In line with this, the purpose of the current study was to quantify the carbon stock in the multifunctional agroforestry landscape designed for small and marginal farmers.

Materials and Methods

Study area

The study was carried out in a circular MFA model at Forest College and Research Institute, Mettupalayam (11˚19' N, 76˚56' E, and 300 m above MSL), situated in the sylvan surroundings of Jakanari reserve forest. The forest cover of the area is classified into tropical deciduous and tropical thorn forest and lies in the western agro-climatic zone of Tamil Nadu, receiving an annual rainfall of 830 mm, mostly from the North-East monsoon along with the South-West monsoon. From December to February, winter lasts longer than usual, while from March to May, summer lasts briefly, with a mean maximum and minimum temperature of 32.2°C and 23.2°C, respectively.

The data was recorded in the 6 yr old MFA system laid out in a circular framework extending an area of 0.75 acres comprising 24 different tree species and 8 intercrops. The area was divided into 4 distinctive quadrats of equal size (Fig. 1). The model was established in 2018, keeping into account different ecosystem services and multiple benefits rendered by agroforestry. Each quadrat has 6 circles (C) spaced at 5 m apart, and each circle has distinct significance, *viz.*, C1-Moringa circle, C2-Fruits circle, C3-Medicinal plants circle, C4-Plywood circle, C5-Timber circle and C6-High value timber circle. The different intercrops include flowers in Quadrat I, vegetables in Quadrat II, curry leaf and nerium in Quadrat III, and fodder in Quadrat IV. The species were selected based on their suitability and multiple utility (8).

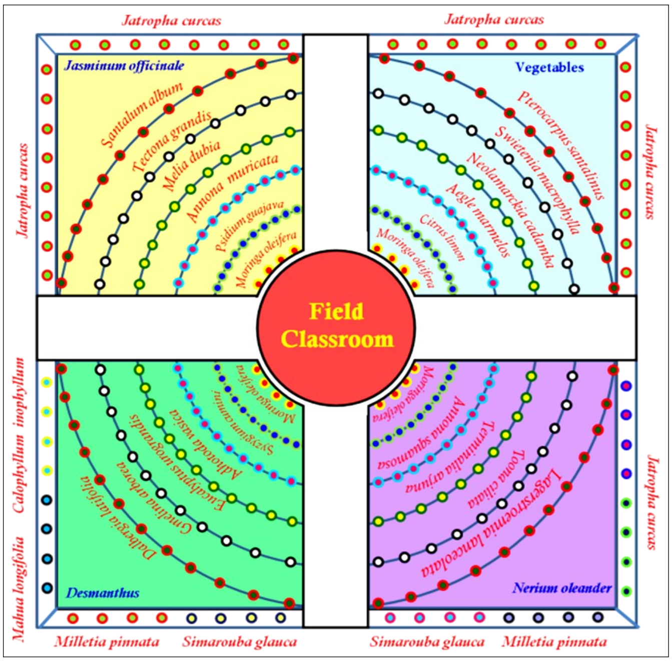

Fig. 1. Layout of circular multifunctional agroforestry system.

The high-value timber circle consisted of *Santalum album* (QI), *Pterocarpus santalinus* (QII) and *Dalbergia latifolia* (QIV). The timber species included *Tectona grandis* (QI), *Swietenia macrophylla* (QII), *Lagerstroemia lanceolata* (QIII) and *Gmelina arborea* (QIV). The plywood circle comprised *Melia dubia* (QI), *Neolamarckia cadamba* (QII), *Toona ciliata* (QIII) and *Eucalyptus urograndis* (QIV). The medicinal plants circle included *Annona muricata* (QI), *Aegle marmelos* (QII), *Terminalia arjuna* (QIII) and *Justicia adhatoda* (QIV). The fruit tree species were *Psidium gujava* (QI), *Citrus limon* (QII), *Annona squamosa* (QIII) and *Syzygium cumini* (QIV). *Moringa oleifera* was planted in all 4 quadrants. The different intercrops included *Jasminum grandiflorum* and *Jasminum officinale* in QI, Vegetable crops (Brinjal, Bhendi, Green chili, Coriander, Palak and Amaranthus) in QII, *Murraya koenigii* and *Nerium oleander* in QIII, Guinea grass and Desmanthus in QIV. The borer trees included tree-borne oil seeds trees, *viz., Jatropha curcas*, *Calophyllum inophyllum*, *Pongamia pinnata*, *Simarouba glauca* and *Madhuca longifolia*.

Measurement of vegetative biomass and carbon stock

Calculation of volume of biomass

A non-destructive method was followed for carbon stock estimation. Vegetative biomass was calculated for all the trees present in each quadrat, including border trees. The biometric parameters, *viz.*, height (m) and girth (over bark) (GBH) at breast height, were calculated using measuring tape and an altimeter. The standing tree volume was calculated as follows:

$$\text{Volume of tree (m}^3\text{)} = (\pi D^2)/4 \times H \times F \quad \text{........(Eqn. 1)}$$

Where D is the diameter of the tree (m), H is the height of the tree (m) and F is the form factor of the tree. The girth of shrub species was recorded by measuring the top and basal girth and the volume was calculated by assuming each branch as a truncated cone.

$$\text{Volume of branch (m}^3\text{)} = 1/3\ \pi\ (r_1^2+r_1 \quad \text{........(Eqn. 2)}$$

$$\text{Volume of shrub (m}^3\text{)} = \sum (V_1+V_2+\cdots+V_n) \quad \text{........(Eqn. 3)}$$

Where r_1 is the radius from top girth and r_2 is the radius from basal girth.

Calculation of weight of biomass

The above ground biomass (ABG) for each tree was calculated as follows:

$$\text{AGB (kg tree}^{-1}\text{)} = \text{Volume (m}^3\text{)} \times \text{Wood specific gravity} \quad \text{........(Eqn. 4)}$$

Using a root: shoot ratio of 0.26, the below-ground biomass was computed, taking into account live root biomass but excluding fine root biomass (11).

$$\text{BGB (kg tree}^{-1}\text{)} = \text{AGB} \times 0.26 \quad \text{........(Eqn. 5)}$$

Determination of total vegetative biomass and carbon stock

The total vegetative biomass (TB) and total carbon stock (TCS) were calculated as per Eqn. 6 and Eqn. 7:

$$\sum \text{TB (kg tree}^{-1}\text{)} = \sum \text{AGB (kg tree}^{-1}\text{)} + \sum \text{BGB (kg tree}^{-1}\text{)} \quad \text{........(Eqn. 6)}$$

$$\sum \text{TCS} = \sum \text{TB} \times \text{tree density} \times \text{carbon content (\%)} \quad \text{........(Eqn. 7)}$$

Quantity of carbon dioxide (CO2)

The weight of one carbon molecule (44 g) divided by the weight of oxygen (12 g) yielded a multiplication coefficient of 3.67. This coefficient was multiplied by the total carbon stock of MFA to obtain the quantity of CO_2.

$$tCO_2 = 3.67 \times \sum \text{TCS} \quad \text{........(Eqn. 8)}$$

Measurement of soil organic carbon

The soil samples were taken at random from all 4 quadrants of the circular MAF model at 3 different soil depths (0–20 cm, 20–40 cm and 40–60 cm) in order to calculate the soil bulk density (g cm^{-3}), soil organic carbon content (SOC%) and soil carbon stock (mg ha^{-1}). The initial soil sample collection was done in December 2023, and the final sample collection was done in June 2024. SOC was ascertained using the wet oxidation method (12), whereas the bulk density of the soil was calculated using the Keen-Raczkowski cup method (13). The computations were performed using the following equation:

$$\text{SOC stock (mg ha}^{-1}\text{)} = \text{SOC (\%)} \times \text{depth (cm)} \times \text{bulk density (g cm}^{-3}\text{)} \quad \text{........(Eqn. 9)}$$

Valuation

The carbon price, as suggested by few researchers, was used in the present study (14).

$$\text{Carbon payment of MFA} = \text{US\$ } 10 \times \quad \text{........(Eqn. 10)}$$

One-way ANOVA and the Duncan's Multiple Range Test (DMRT) were carried out in SPSS IBM software and were used to assess any significant differences between the quadrats (15, 16).

Results

Growth and biomass of trees and shrubs from MFA

The descriptive statistics analyses indicated that the mean height ranged from 3.36 m to 11.04 m and the mean DBH ranged from 7.08 cm to 17.37 cm. *Neolamarckia cadamba* had the highest mean height and DBH of all the tree species in MFA, measuring 11.04 m and 17.37 cm, respectively. *Melia dubia* registered the second-highest mean height and DBH at 8.27 m and 15.11 cm, followed by *Swietenia macrophylla* at 7.74 m and 12.82 cm, respectively. Among the shrub species, the highest mean basal girth was recorded in *Madhuca latifolia* (41.78 cm), followed by *Terminalia arjuna* (36.84 cm), whereas the lowest was recorded in *Annona muricata* (7.04 cm) and *Jatropha curcas* (9.55 cm). Significant differences were noted in biomass and carbon stock for different trees of MFA. *N. cadamba* recorded significantly higher biomass (165.20 ± 3.91 kg $tree^{-1}$), followed by *M. dubia* (78.06 ± 3.07 kg $tree^{-1}$), *Lagerstoemia lanceolata* (66.94 ± 2.53 kg $tree^{-1}$) and *Swietenia macrophylla* (61.27 ± 1.18 kg $tree^{-1}$), whereas *Annona muricata* (0.34 ± 0.12 kg $tree^{-1}$) was found to have lower biomass, followed by *Justicia adhatoda* (0.41± 0.04 kg $tree^{-1}$), *Eucalyptus urograndis* (0.48 ± 0.29 kg $tree^{-1}$) and *Citrus limon* (1.02 ± 0.11 kg $tree^{-1}$) (Table 1).

Vegetation carbon stock

The average carbon stock (above ground and below ground) showed significant variation among the different tree species (Table 1). Among all the species, *N. cadamba* recorded the highest above and below-ground carbon stock (70.65 ± 2.40 kg $tree^{-1}$; 18.37 ± 0.35 kg $tree^{-1}$). In high-

Table 1. Biometric data, biomass and carbon stock (above and below ground) of different species of MFA.

Circle	Species	Mean height (m)	Mean DBH (cm)	Mean basal girth	Average above ground biomass (kg tree^{-1})	Average carbon stock (kg tree^{-1})		Carbon sequestration rate (kg tree^{-1} yr^{-1})
						AGB -C	BGB-C	
High value timber	*Santalum album*	3.36	7.08	-	12.04 ± 0.71^{c}	5.20 ± 0.33^{c}	1.35 ± 0.86^{b}	1.09
	Pterocarpus santalinus	4.55	7.76	-	18.91 ± 0.58^{b}	7.69 ± 0.52^{b}	2.00 ± 0.23^{b}	1.61
	Dalbergia latifolia	6.22	9.98	-	41.34 ± 0.74^{a}	16.86 ± 1.21^{a}	4.38 ± 0.22^{a}	3.54
Timber	*Tectona grandis*	7.39	12.43	-	56.77 ± 1.71^{c}	21.33 ± 1.08^{c}	5.55 ± 0.18^{bc}	4.48
	Swietenia macrophylla	7.73	12.82	-	61.27 ± 1.18^{b}	24.86 ± 0.65^{b}	6.46 ± 0.22^{ab}	5.22
	Lagerstoemia lanceolata	7.41	14.02	-	66.94 ± 2.53^{a}	29.12 ± 1.33^{a}	7.57 ± 0.38^{a}	6.11
	Gmelina arborea	6.98	9.11	-	32.90 ± 1.26^{d}	14.78 ± 0.98^{d}	3.84 ± 0.47^{c}	3.10
Plywood	*Melia dubia*	8.27	15.11	-	78.06 ± 3.07^{b}	32.61 ± 1.43^{b}	8.48 ± 0.62^{b}	6.85
	Neolamarckia cadamba	11.04	17.37	-	165.20 ± 3.91^{a}	70.65 ± 2.40^{a}	18.37 ± 0.35^{a}	14.84
	Toona ciliate	5.98	9.95	-	29.13 ± 2.84^{c}	12.59 ± 0.81^{c}	3.27 ± 0.33^{c}	2.64
	Eucalyptus urograndis	2.00	1.96	-	0.48 ± 0.29^{d}	0.21 ± 0.11^{d}	0.06 ± 0.49^{d}	0.04
Medicinal	*Annona muricata*	1.13	-	7.04	0.34 ± 0.12^{c}	0.16 ± 0.05^{c}	0.04 ± 0.05^{c}	0.03
	Aegle marmelos	3.48	-	23.34	5.43 ± 0.78^{b}	2.33 ± 0.11^{b}	0.61 ± 0.07^{b}	0.49
	Terminalia arjuna	4.08	-	36.84	14.79 ± 2.90^{a}	5.93 ± 0.99^{a}	1.54 ± 0.43^{a}	1.24
	Justicia adhatoda	1.33	-	9.61	0.41 ± 0.04^{c}	0.16 ± 0.02^{c}	0.04 ± 0.02^{c}	0.03
Fruits	*Psidium gujava*	4.16	-	20.73	12.56 ± 0.68^{b}	5.15 ± 0.23^{b}	1.34 ± 0.10^{a}	1.08
	Citrus limon	2.11	-	16.19	1.02 ± 0.11^{c}	0.45 ± 0.05^{c}	0.12 ± 0.04^{b}	0.09
	Annona squamosa	2.51	-	14.45	1.57 ± 0.24^{c}	0.68 ± 0.09^{c}	0.18 ± 0.08^{b}	0.14
	Syzygium cumini	4.12	-	38.55	17.53 ± 1.08^{a}	7.68 ± 0.54^{a}	2.00 ± 0.11^{a}	1.61
Moringa	*Moringa oleifera*	5.76	21.52	-	21.56 ± 2.76	7.84 ± 1.02	2.04 ± 0.24	1.65
TBO'S	*Jatropha curcas*	1.28	-	9.55	1.04 ± 0.31^{c}	0.39 ± 0.08^{d}	0.10 ± 0.06^{c}	0.08
	Pongamia pinnata	3.39	-	32.88	6.47 ± 0.24^{a}	2.64 ± 0.87^{b}	0.69 ± 0.11^{a}	0.55
	Simarouba glauca	4.71	-	34.43	4.08 ± 0.40^{b}	1.75 ± 0.24^{c}	0.45 ± 0.09^{b}	0.37
	Madhuca longifolia	3.38	-	41.78	7.04 ± 1.18^{a}	2.88 ± 0.51^{a}	0.75 ± 0.14^{a}	0.60
	Calophyllum inophyllum	4.51	-	22.13	6.05 ± 0.87^{a}	2.57 ± 0.22^{b}	0.67 ± 0.10^{a}	0.54
					Mean			2.32

Biomass and carbon stock values are represented as Mean ± SD. According to DMRT, the average values with same superscript within each column are not significant ($p<0.01$). (**DBH** - Diameter at breast height; **AGB-C** - Above ground biomass carbon; **BGB-C** - Below ground biomass carbon).

value timber circle, *Dalbergia latifolia* recorded the highest above and below ground biomass (16.86 ± 1.21; 4.38 ± 0.22 kg tree^{-1}). All the high-value timber species, *viz*., *Santalum album* (5.20 ± 0.33 kg tree^{-1}), *Pterocarpus santalinus* (7.69 ± 0.52 kg tree^{-1}) and *Dalbergia latifolia* registered significant differences in the above-ground carbon stock. Among the timber trees, *L. lanceolata* (29.12 ± 1.33; 7.57 ± 0.38 kg tree^{-1}) recorded maximum above and below ground carbon stock and all 4 species, *viz*., *Tectona grandis*, *Swietenia macrophylla*, *Gmelina arborea* and *L. lanceolata,* recorded significantly different above-ground carbon stock (Table 1). Within the plywood circle, *N. cadmba* recorded the highest above and below ground carbon stock (70.65 ± 2.40; 18.37 ± 0.35 kg tree^{-1}), and all the trees in this circle, *viz*., *M. dubia*, *N. cadamba*, *Toona ciliata* and *E. urograndis,* recorded significant differences in carbon stock (Table 1.)

T. arjuna (5.93 ± 0.99; 1.54 ± 0.43 kg tree^{-1}) was found to have maximum above and below-ground carbon stock in the medicinal circle, whereas 2 species, *viz*., *A. muricata* (0.16 ± 0.05; 0.04 ± 0.05 kg tree^{-1}) and *J. adhatoda* (0.16 ± 0.02; 0.04 ± 0.02 kg tree^{-1}) were found to be on par with each other. Among the fruit circle, significantly higher above and below-ground carbon stock was found in *Syzygium cumini* (7.68 ± 0.54; 2.00 ± 0.11 kg tree^{-1}) along with *Psidium gujava* (5.15 ± 0.23; 1.34 ± 0.10 kg tree^{-1}). However, the other 2 species (*Citrus limon* and *Annona squamosa*) were found to have insignificantly lower carbon stock (Table 1). In border trees, *Madhuca longifolia* recorded maximum above and below-ground carbon stock (2.88 ± 0.51; 0.75 ± 0.14 kg tree^{-1}) but had insignificant below-ground carbon stock. The lowest carbon stock was registered in *J. curcas* (0.39 ± 0.08; 0.10 ± 0.06 kg tree^{-1}) (Table 1).

Total carbon sequestration

The total carbon sequestered from multifunctional agroforestry comprising 316 multi-utility trees and shrubs in the 0.75 acres of land was 43.82 tons (3823.94 kg) (Table 2). Significant variations between the 4 quadrats and boundary trees were revealed by a one-way ANOVA. Among the different species, maximum total carbon sequestration

Table 2. Total carbon sequestration in different quadrats of MFA.

Quadrats	Tree components	Tree density	Total carbon stock (kg)	CO_2e (kg)
I	*Santalum album*	12	78.68[c]	288.74
	Tectona grandis	12	322.50[a]	1183.59
	Melia dubia	7	287.59[b]	1055.45
	Annona muricata	5	0.98[f]	3.60
	Psidium gujava	11	71.44[d]	262.18
	Moringa oleifera	2	39.49[e]	144.92
Total		49	800.68	2938.48
II	*Pterocarpus santalinus*	8	77.50[c]	284.43
	Swietenia macrophylla	12	375.94[b]	1379.70
	Neolamarckia cadamba	12	1068.29[a]	3920.62
	Aegle marmelos	11	32.33[e]	118.67
	Citrus limon	5	2.85[f]	10.45
	M. oleifera	2	34.94[d]	128.23
Total		50	1591.85	5842.09
III	*Lagerstroemia lanceolata*	12	440.25[a]	1615.72
	Toona ciliata	9	142.83[b]	524.17
	Terminalia arjuna	11	82.14[c]	301.45
	A. squamosa	9	7.71[e]	28.31
	M. oleifera	3	58.20[d]	213.58
Total		44	731.13	2683.24
IV	*Dalbergia latifolia*	10	212.48[b]	779.78
	Gmelina arborea	12	223.41[a]	819.91
	Eucalyptus urograndis	10	2.69[e]	9.87
	Justicia adhatoda	5	1.02[f]	3.73
	Syzygium cumini	10	96.74[c]	355.05
	M. oleifera	2	31.65[d]	116.16
Total		49	567.99	2084.51
Border	*Jatropha curcas*	96	47.14[a]	172.99
	Pongamia pinnata	10	33.27[b]	122.10
	Simarouba glauca	8	17.60[cd]	64.57
	Madhuca longifolia	5	18.13[c]	66.52
	Calophyllum inophyllum	5	16.17[d]	59.36
Total		124	132.30	485.54
Total (0.75 acre)		316	3823.94 (3.82 tons)	14033.85 (14.03 tons)
Carbon revenue (Carbon price: US$ 10 per tCO_{-2})				US$ 140.3

According to DMRT, the values of total carbon stock with different superscript are significant ($p<0.01$).

(TCS) was reported in *N. cadamba* (1068.29 kg from 12 trees), followed by *L. lanceolata* (440.25 kg from 12 trees) and *S. macrophylla* (375.94 kg from 12 trees) (Table 2). Out of the 4 quadrants, Quadrat II had the highest TCS (1591.85 kg), whereas Quadrat I had the lowest TCS (800.68 kg), with tree densities of 50 and 49, respectively. In Quadrat I, *Tectona grandis* registered significantly the highest TCS (322.50 kg), followed by *M. dubia* (287.59 kg). The maximum contribution of TCS in Quadrat II was majorly from *N. cadamba* (1068.29 kg) and *S. macrohylla* (375.94 kg).

The TCS from Quadrat III was 731.13 kg with a tree density of 44. The maximum carbon was sequestered significantly by *L. lanceolata* (440.25 kg), followed by *Dalbergia latifolia* (212.48 kg) (Table 2). A total of 567.99 kg of carbon was sequestered from Quadrat IV with a tree density of 49. The maximum TCS was recorded in *Gmelina arborea* (223.41 kg) and varied significantly along with *D. latifolia* (212.48 kg) and *S. cumini* (96.74 kg), respectively. The lowest TCS was found in border trees (132.30 kg from 124 trees) compared to all 4 quadrats. Among the border trees, *J. curcas* (47.14 kg) recorded the highest TCS and differed significantly along with *Pongamia pinnata* (33.27 kg), *Madhuca longifolia* (18.13 kg) and *Calophyllum inophyllum* (16.17 kg), whereas *Simarouba glauca* (17.60 kg) differed insignificantly. The total carbon revenue from the vegetation summed up to \$140.3 (Rs.11776.98) (Table 2).

Soil organic carbon

The greatest SOC stock was found in the top layer of the soil (0–20 cm) in all 4 quadrants and the SOC stock declined as the soil depth increased. The total change in the soil organic carbon stock was 12.99 mg ha^{-1} (4.68 mg $quadrat^{-1}$) from MFA. Significant variation in soil organic carbon was observed among the quadrats but was insignificant across the soil depths ($p<0.01$). Maximum SOC stock (initial and final) was observed in Quadrat IV (37.79 and 37.25 mg $quadrat^{-1}$), followed by Quadrat II (33.53 and 34.61 mg $quadrat^{-1}$). The total CO_2e was 17.17 mg $quadrat^{-1}$ and the average soil carbon sequestration rate recorded in MFA was 0.18 mg ha^{-1} yr^{-1}. The total marketable soil carbon revenue from the MFA was \$171.1 (Rs.14363.74) (Table 3).

Discussion

Biomass and carbon stock of MFA

The results reveal significant variations in growth characteristics and carbon storage potential among tree and shrub species in the MFA system. *Neolamarckia cadamba* demonstrated superior performance in height, DBH and biomass accumulation, aligning with its known rapid growth traits (17). *Melia dubia* and *Swietenia macrophylla* also showed substantial growth, consistent with their potential in agroforestry systems (18). Among shrubs, *Madhuca latifolia*'s large basal girth reflects its ecological importance in traditional agroforestry (19). The significant differences in biomass and carbon stock among species underscore the importance of species selection in forest management and carbon sequestration projects. *N. cadamba*'s high biomass supports its potential for carbon sequestration (20), while the lower biomass of species like *Annona muricata* highlights the diverse roles different species play in mixed forest ecosystems. These findings align with recent research emphasizing the impact of species-specific traits on forest carbon storage (21) and the benefits of mixed-species plantations (22). This data provides valuable insights for optimizing species selection in forest management, agroforestry and carbon sequestration initiatives.

Table 3. Change in soil organic carbon at different depths of MFA.

Quadrats	Soil depth (cm)	Initial soil carbon stock		Final soil carbon stock		Change in soil carbon over 7 months		CO_2e (mg quadrat^{-1})	Soil carbon sequestration rate (mg ha^{-1} yr^{-1})
		mg ha^{-1}	mg quadrat^{-1}	mg ha^{-1}	mg quadrat^{-1}	mg ha^{-1}	mg quadrat^{-1}		
I	0–20	28.69 ± 0.89	10.33 ± 0.43^{cdef}	30.04 ± 1.21	10.81 ± 0.23^{bc}	1.35	0.49	4.63	0.23
	20–40	27.51 ± 1.03	9.90 ± 0.55^{def}	28.49 ± 0.77	10.26 ± 0.72^{bcd}	0.98	0.35		0.16
	40–60	25.94 ± 0.46	9.34 ± 0.31^{ab}	27.11 ± 0.81	9.76 ± 0.11^{cd}	1.17	0.42		0.20
	Total	82.14	29.57	85.64	30.83	3.50	1.26		-
II	0–20	37.34 ± 1.87	13.44 ± 0.16^{bc}	38.97 ± 1.19	14.03 ± 0.23^{a}	1.63	0.59	3.96	0.27
	20–40	29.87 ± 1.23	10.75 ± 0.21^{f}	30.54 ± 0.85	10.99 ± 1.09^{bc}	0.67	0.24		0.11
	40–60	25.94 ± 1.18	9.34 ± 0.22^{def}	26.63 ± 0.39	9.59 ± 1.11^{cd}	0.69	0.25		0.12
	Total	93.14	33.53	96.14	34.61	3.00	1.08		-
III	0–20	27.12 ± 0.47	9.76 ± 0.41^{f}	28.21 ± 1.02	10.16 ± 0.61^{bcd}	1.09	0.39	3.25	0.18
	20-40	25.15 ± 0.51	9.05 ± 0.19^{ef}	25.94 ± 0.34	9.34 ± 0.92^{cd}	0.79	0.28		0.13
	40-60	23.58 ± 0.62	8.49 ± 0.29^{a}	24.16 ± 0.87	8.70 ± 1.01^{cd}	0.58	0.21		0.10
	Total	75.85	27.31	78.31	28.19	2.46	0.89		-
IV	0-20	37.34 ± 1.66	13.44 ± 0.22^{bcd}	38.78 ± 1.28	13.96 ± 0.93^{a}	1.44	0.52	5.33	0.24
	20-40	31.44 ± 1.08	11.32 ± 0.54^{bcde}	32.86 ± 1.19	11.83 ± 0.78^{b}	1.42	0.51		0.24
	40-60	30.65 ± 0.91	11.04 ± 0.49^{g}	31.82 ± 1.05	11.46 ± 0.34^{b}	1.17	0.42		0.19
Total		99.43	35.79	103.46	37.25	4.03	1.45		-
Total change in SOC stock						12.99	4.68	17.17	-
Marketable carbon price (US$ 10 per tCO_2)								$171.1	-
Average soil C sequestration rate									0.18

Data represented as Mean ± SD. According to DMRT, the values within each column with same superscript are insignificant ($p<0.01$).

The study revealed that the biomass from MFA ranged from 0.34 kg tree^{-1} (*A. muricata*) to 165.20 kg tree^{-1} (*N. cadamba*) (Table 1). Panwar et al. (5) noted the significant differences in the total biomass from different agroforestry systems of India, indicating that the block plantations had the highest AGB (109.8 mg ha^{-1}) and the home gardens had the highest BGB (34.68 mg ha^{-1}). The total biomass varied in a decreasing order as follows: plantation crop-based agroforestry, block plantations, home gardens, agri-horticulture, silvi-pasture, agri-silviculture and boundary plantations. A similar study regarding biomass of different agroforestry systems was reported by Kumara et al. (23). Significant differences were registered in terms of biomass and C stock (ABG-C and BGB-C) in the high-value timber circle consisting of 3 species, *viz., Dalbergia latifolia*, *Pterocarpus santalinus* and *Santalum album* (Table 1). These species possess high wood-specific gravity and densities, hence contributing to the storage of carbon in the long term. The significant differences observed among high-value timber species underscore the importance of species-specific traits in carbon accumulation, as emphasized by Xu et al. (24). Venkatesh et al. (25), Chopra et al. (26) and Singh (27) emphasized the potential of sandalwood, rosewood and red sander-based systems and plantations in different regions of the country for carbon sequestration, highlighting them as one of the most promising options for storing carbon both in plants and in soil.

In timber and plywood circles, the highest biomass and C stock were registered in *Lagerstroemia lanceolata* (66.94 kg and 29.12 kg tree^{-1}) and *N. cadamba* (165.20 kg and 70.65 kg tree^{-1}), respectively (Table 1), owing to their maximum height and DBH compared to other species in respective circles. The dendrometric parameters, such as height and DBH, show a strong linear correlation with carbon stock (28). Comparable findings demonstrating the importance of dendrometric factors in the fluctuation of total carbon stocks within agroforestry systems were reported by Kumar et al. (29) and Rizvi et al. (30). *N. cadamba*'s exceptional carbon storage capacity aligns with recent findings by Chavan et al. (31), who reported its high potential for carbon sequestration in agroforestry systems. The superior performance of *L. lanceolata* among timber trees supports recent research by Arya et al. (32) on the carbon sequestration potential of fast-growing native species. The variation in carbon stock among plywood species further reinforces the need for careful species selection in plantation forestry, as discussed by Behera et al. (33) in their study of tropical tree species for climate change mitigation.

In the medicinal circle, *Terminalia arjuna*'s higher carbon stock aligns with recent studies on the multifunctional benefits of native medicinal trees in agroforestry (34). The fruit circle showed significant variations in biomass and C stock with *Syzygium cumini* contributing the highest, followed by *Psidium gujava*, *Annona squamosa* and *Citrus limon* (Table 1). The performance of fruit trees demonstrates the potential for combining carbon sequestration with food production, a key aspect of climate-smart agroforestry (35). Similarly, Singh et al. (36) reported the potential of diverse horticulture and fruit-based agroforestry systems in Mirzapur, India, which can sequester up to 2.11 tons of carbon per ha per year and hence help farmers establish mutually beneficial relationships between livelihood stability and climate change mitigation.

Carbon sequestration from MFA

The significant variations in total carbon sequestration (TCS) among the 4 quadrats and boundary trees highlight the importance of spatial heterogeneity and species composition in agroforestry systems. Quadrat II, with the highest TCS, likely benefits from a combination of favorable site conditions and a mix of high-sequestering species like *N. cadamba* and *S. macrophylla*. Conversely, Quadrat I, with the lowest TCS, might be constrained by factors such as soil quality, competition, or less efficient species. The variation in TCS among species is primarily attributed to their growth rates, biomass accumulation and carbon allocation patterns. *N. cadamba*, known for its rapid growth and high biomass production, consistently exhibited the highest TCS. Species like *L. lanceolata* and *S. macrophylla* also demonstrated notable sequestration potential.

The maximum contribution of carbon sequestration was recorded in Quadrat II (1591.85 kg), wherein the maximum contribution was from *N. cadamba* (67.1%), followed by Quadrat I (800.68 kg), majorly from *Tectona grandis* (40.3%) (Fig. 2). The significant biomass carbon sequestration potential of Cadamba (81.90 tonne ha^{-1} and 39.31 tonne ha^{-1}) in Indonesia's 8 year old forest plantation was reported by Sarjono et al. (37). The highest contribution to carbon sequestration was from *L. lanceolata* (60.2%) and *Gmelina arborea* (39.3%) in Quadrat III and IV, respectively (Table 2) (Fig. 2). As indicated by Baul et al. (38), trees have the highest value of biometric parameters (tree density, DBH), which may account for the majority of their contribution to carbon sequestration. The highest CO_2e was registered in Quadrat II (2683.24 kg) due to the presence of fast-growing trees such as *N. cadamba*. Compared to the nation's ability to sequester carbon (0.21 mg C ha^{-1} yr^{-1}) (39), the MFA recorded a mean carbon sequestration rate of 2.32 kg $tree^{-1}$ (Table 1).

The boundary trees, despite their higher density, sequestered significantly less carbon than the quadrats. This could be due to factors such as edge effects, competition with surrounding vegetation, or less favorable microclimates. However, species like *Jatropha curcas* and *Pongamia pinnata* showed promising sequestration capabilities even in the boundary zone.

Soil carbon sequestration and valuation from MFA

The concentration of soil organic carbon (SOC) tends to be higher in the topsoil due to greater organic matter input from plant residues and microbial activity. The decline in SOC with depth is likely attributed to lower organic matter

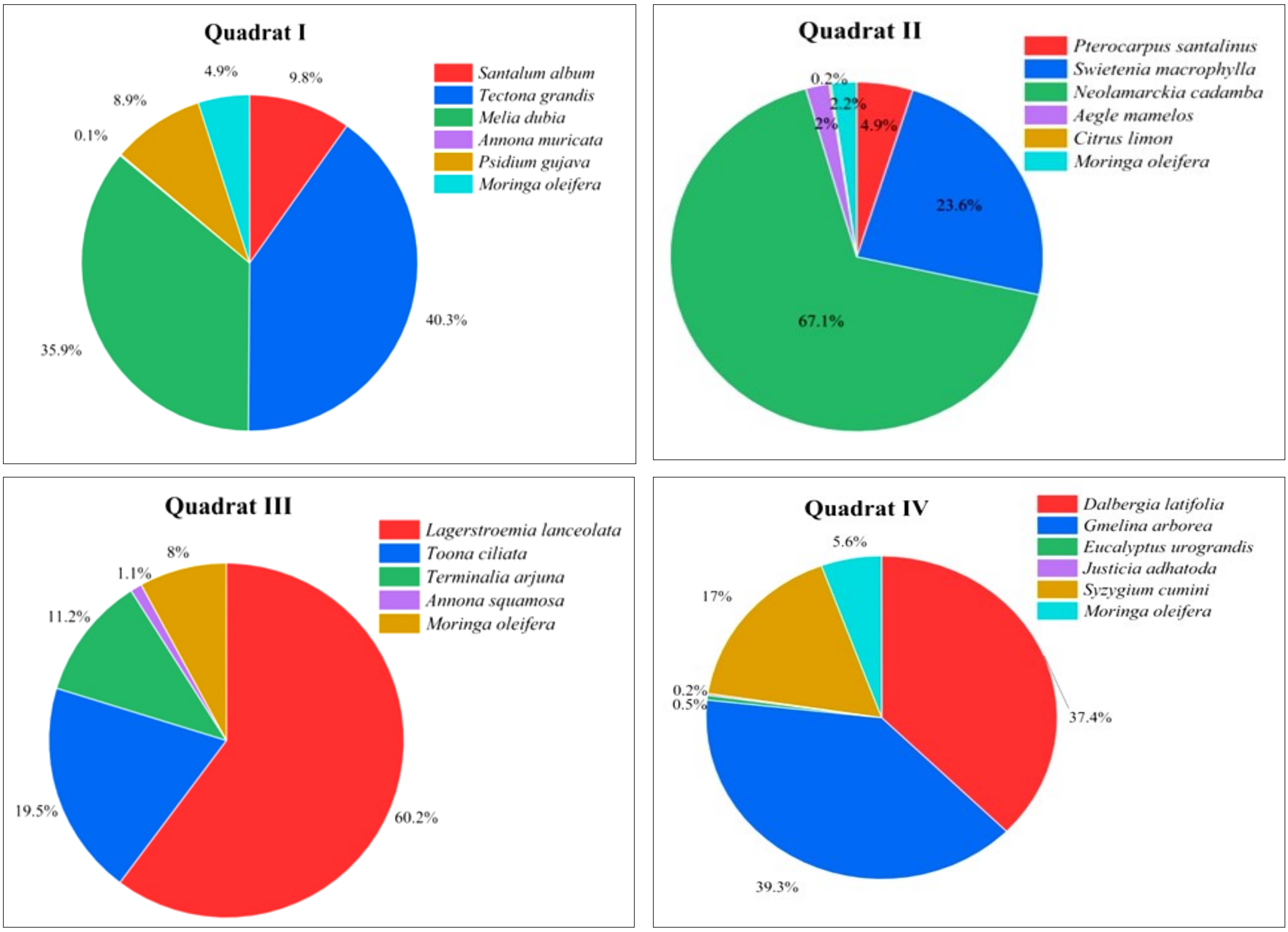

Fig. 2. Total carbon stock (kg $quadrat^{-1}$) in different quadrats of multifunctional agroforestry system.

decomposition rates and reduced microbial activity in deeper layers. The variation in SOC stock among quadrats suggests that factors such as initial soil conditions, tree species composition, and management practices influence carbon sequestration. Quadrat IV, with the highest SOC stock, may benefit from favorable conditions for organic matter accumulation and microbial activity.

The highest soil CO_2e was recorded in Quadrat IV (5.33 mg quadrat^{-1}; Table 3), possibly resulting from the intercrops present (Guinea grass and Desmanthus), which enhance SOC through litter and root turnover. Further, it is also influenced by temperature, rainfall, litterfall and existing microclimatic conditions (23). The SOC was found to be the highest at soil depth 0–20 cm in all 4 quadrants. The results are consistent with the earlier work by Singh et al. (40), in which the poplar-based agroforestry system in Bihar had the greatest total SOC stock in the 0–15 cm soil profile (18.18 mg C ha^{-1}). Analogous research has been conducted in many global locations (41–43). The observed CO_2e emissions and carbon sequestration rate indicate that MFA contributes to carbon mitigation. However, further research is needed to quantify the long-term carbon sequestration potential of MFA under different environmental conditions and management practices.

An initiative within the REDD+ framework aims to promote long-term sustainable land use and carbon conservation by encouraging smallholders to adopt agroforestry practices. This approach can significantly improve the economic situation of smallholder farmers, particularly in developing nations (44). According to the current analyses, MFA has a potential revenue stream of US$ 325.8 (with US$ 154.7 from vegetation and US$ 171.1 from soil).

Conclusion

The substantial potential of integrated multifunctional agroforestry systems in carbon sequestration and climate change mitigation has been shown in the current study. The MFA, comprising 316 multi-utility and shrubs spanning over an area of 0.75 acres, was found to sequester a total of 3.82 tons of carbon. The total carbon revenue from the vegetation and soil was estimated at US$ 311.4 (US$ 140.3 from vegetation and US$ 171.1 from soil), highlighting the economic benefits of such systems for small and marginal farmers. The integration of diverse tree species with intercrops in a circular layout maximizes the utilization of available resources and provides multiple ecosystem services. The current study offers insightful information to practitioners, researchers and policymakers to encourage the broad use of MFA systems to improve carbon sequestration and the lives of marginal and small-scale farmers. The future scope of this study lies in the potential expansion of MFA systems across different agroecological regions, exploring their long-term performance and investigating the underlying mechanisms that drive carbon sequestration in these integrated systems. Additionally, the development of robust monitoring and evaluation frameworks, as well as the integration of MFA systems into national and international carbon markets, can further enhance the economic incentives for small and marginal farmers to adopt these sustainable practices. Ultimately, the implementation of MFA systems on a large scale has the potential to greatly improve the security of food, reduce the effects of climate change and enhance the general welfare of rural populations in developing nations.

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Authors' contributions

PMR carried out the experiment and drafted the original manuscript. IS and KTP conceptualized the idea for the study, designed the study and reviewed the manuscript. SVR reviewed and participated in editing of the manuscript. FMA and DS helped in the statistical analysis of the study. MK was involved in investigation and supervision. MSS participated in the revision and editing of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None.

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