Quantification and economic valuation of carbon sequestration from smallholder multifunctional agroforestry: a study from the foothills of the Nilgiris, India

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Agroforestry is widely recognized for its role in climate change mitigation and adaptation. However, carbon sequestration and a marketable carbon value of smallholder agroforestry systems in India are poorly documented. Therefore, the present study was carried out to quantify carbon stock in a circular-shaped multifunctional agroforestry (MFA) divided into four equal quadrats. It comprises 24 different tree species and 8 intercrops, mainly established to provide daily income to small and marginal farmers. A nondestructive method was used to assess biomass carbon stock. Soil core samples collected from 0 to 60 cm depth were analysed to quantify soil organic carbon (SOC) stock. Results revealed significantly higher biomass and carbon stock in the following order: *Neolamarckia cadamba* > *Melia dubia* > *Lagerstroemia parviflora* > *Dalbergia latifolia* > *Tectona grandis*. Duncan's multiple range test revealed significant differences in the multi-utility circles ($P < 0.001$). The total change in SOC stock was 11.55 Mg quadrat^{-1}, but the difference was insignificant in different soil depths. The results indicated that the total carbon sequestration and CO_{2e} from vegetation were 2.23 and 9.23 tonnes respectively. Similarly, CO_{2e} from the soil were 42.37 Mg quadrat^{-1} respectively; the highest contributions were from quadrat II and quadrat IV of MFA. By taking into account profitability and incentives to smallholder farmers, the total marketable carbon revenue of MFA was calculated as US$ 206.40.

Keywords: Biomass carbon stock, multifunctional agroforestry, soil organic carbon, total carbon sequestration.

GLOBAL atmospheric carbon dioxide (CO_2) has touched 400 ppm and is predicted to reach between 700 and 900 ppm in the coming years due to industrialization[1]. India is the third-largest emitter of greenhouse gases (GHGs), after China and the United States[2]. According to the Nationally Determined Contributions (NDCs), the United Nations Framework on Climate Change (UNFCCC), India's emissions are projected to rise by 3.8–5.3 Pg CO_2 eq by 2030 (ref. 3). Moreover, among different land-use systems, agriculture, forestry and associated land-use contribute to increasing GHG emissions, accounting for 13% of CO_2, 44% of methane (CH_4), and 81% of nitrous oxide (N_2O) due to anthropogenic activities[4].

Agroforestry is explicitly recognized in this context for its role in climate change mitigation and adaptation. It has evolved from the science of biophysical interactions between trees, crops, livestock and soils, both above and below ground[5], intending to create climate-smart landscapes that increase productivity and sustainability. Globally, agroforestry accounts for 1020 m ha in area[6]. In India, it is estimated to be 28.03 m ha (ref. 7). The area under agroforestry will expand in the near future and is estimated to be 53.32 m ha in 2050 (ref. 8). In one of the recent projections of carbon sequestration potential, the total biomass carbon and soil stock were high in the agrisilvipastoral system (73.4 and 53.0 Mg C ha^{-1} respectively) followed by the agrisilvicultural system (42.6 and 44.1 Mg C ha^{-1} respectively) and the silvopastoral system (42.7 and 33.5 Mg C ha^{-1} respectively)[3]. In addition, the carbon sequestration potential of smallholder agroforestry systems ranged from 1.5 to 3.5 Mg C ha^{-1} year^{-1} (ref. 9). A mere 30% expansion in the area of agroforestry is projected to reduce India's emissions by 2050 (ref. 10). A total of 23 countries have proposed agroforestry as a mitigation priority and 29 countries have proposed it as an adaptation priority for their NDCs[11]. India has also agreed to cut down emission intensity by 33–35% from 2005 levels by the year 2030, and additionally sequester 2.5–3.0 billion tonnes of carbon through carbon sink[12] for which agroforestry species is the only natural pump which can help achieve the target within the stipulated time. In line with this, India and Nepal have a National Agroforestry Policy (NAP) that supports smallholder farmers[13]. Although agroforestry has not been designed for carbon sequestration, it has been identified by national and international organizations for its major role in carbon storage

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in vegetation and soil. Therefore, it has become necessary to reorient farming practices, viz. multifunctional agroforestry (MFA) landscapes, providing services for improving productivity, storing carbon, providing livelihood security, and income to small farmers mainly under the influence of climate change[14]. Beyond that, the delineated values for carbon sequestration deal with the agroforestry system, consisting of one or two components. However, MFA deals with 24 different tree components in six multi-utility circles providing sustenance to family farming. Furthermore, there is a lack of documentation on carbon storage in small farm agroforestry[15] and its contribution in reducing global emissions[16]. The lack of such information may mislead policymakers to support the inclusion and promotion of small farm agroforestry in climate change discussions[17]. With this background, the present study aimed to quantify carbon stock in MFA landscapes established for small and marginal farmers.

Materials and methods

Study area

The study was conducted in the sylvan surroundings at the foothills of the Nilgiris in the Forest College and Research Institute, Mettupalayam (11°19′33″N, 76°56′16″E, 300 m amsl) in the western agroclimatic zone of Tamil Nadu, India, with an annual rainfall of 750–920 mm. The area receives rainfall from both the southwest and northeast monsoons. Winter starts in December and lasts up to February with an average temperature of 15–18°C. Summer is brief from March to May, with a maximum of 42°C and a minimum of 30°C.

The four-year-old, circular-shaped MFA landscape covers an area of 0.75 acres. It is divided into four equal quadrats, and comprises 24 tree species and 8 intercrops. Each circle of tree species within the model has separate importance, viz. high-value timber circle (sixth), timber circle (fifth), plywood (fourth), medicinal value (third), fruits (second), Moringa circle (first), and border consisting of trees-borne oilseeds (TBOs). The espacement between the circles is 5 m. Figure 1 shows the components included in the circular model. Quadrat I contains *Jasminum grandiflorum* and *Jasminum officinale*, quadrat II contains vegetables (cropping pattern changes for *kharif* and *rabi* seasons), quadrat III contains *Murraya koengii* and *Nerium oleander*, and quadrat IV contains fodder such as Guinea grass (*Megathyrus maximus*) and Desmanthus (*Desmanthus virgatus*).

Measurement of biomass and carbon stock

Calculation of biomass volume: Since the field was established to obtain income and food security for small-scale farmers, a non-destructive method was followed for carbon stock estimation. All the trees present in each quadrat were considered for measurement of biomass. Girth (over bark) in each quadrat was measured using a measuring tape at 1.37 m breast height. The height of the trees (m) present in the four quadrats and the border were measured with a height pole. The volume of a standing tree was calculated as shown in eq. (1).

$$\text{Volume of tree } (m^3) = \pi r^2 h, \quad (1)$$

where r is the radius and h is the height of the tree.

For shrub species, the girth (cm) was measured at two places of each branch – basal girth and top girth – the volume was estimated by considering each branch as a truncated cone as given in eq. (2).

$$\text{Volume of branch } (m^3) = \frac{1}{3}\pi(r_1^2 + r_1 r_2 + r_2^2)h, \quad (2)$$

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

$$\text{Volume of shrub} = \sum (V_1 + V_2 + V_3 + \ldots + V_n), \quad (3)$$

Calculation of biomass weight: Above ground biomass (AGB) of each tree was estimated using the following formula

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

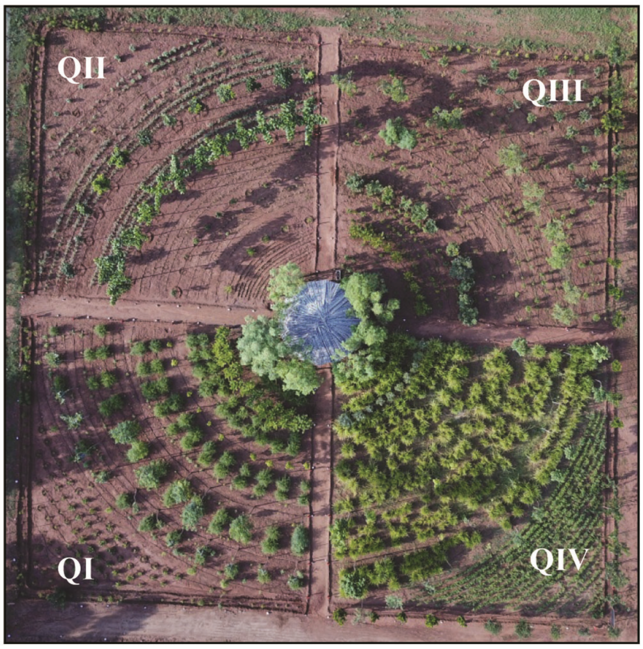

Figure 1. Aerial view of multifunctional agroforestry (MFA) in the foothills of Nilgiris, Tamil Nadu, India.

WSG was estimated by water displacement method as given in the literature[18,19].

Belowground biomass (BGB) includes live root biomass, excluding fine roots and is calculated using a root : shoot ratio of 0.26 (ref. 20).

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

Determination of biomass carbon stock: Total biomass (TB) is the sum of AGB and BGB of both trees and shrubs in MFA.

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

Carbon stock (TCS) was estimated as follows

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

Carbon content (CC) was estimated by combusting 2 g of powdered wood samples in a muffle furnace at 575°C for 3 h (ref. 21).

Soil organic carbon

The soil belongs to Inceptisol and textural class of the soil is sandy loam and non-calcareous. The initial and final soil samples were collected randomly from three different depths (0–20, 20–40 and 40–60 cm) in four different quadrats of MFA. The Walkley and Black[22] method was used to estimate SOC, and total SOC stock was determined. For bulk density, a separate soil core was collected using a core sampler.

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

Quantity of carbon dioxide

CO_2 contained in the total carbon stock of MFA was multiplied by 3.67 (44/12). It is the ratio of the total weight of one molecule of carbon (44 g) to oxygen (12 g). Therefore, total CO_2 was calculated

$$\text{tCO}_2 = 3.67 \times \sum \text{TCS}.$$

Valuation

The carbon price as suggested by Neya *et al.*[23] for smallholder farmers was used in the present study

$$\text{Carbon payment system of MFA} = \text{US\$ } 4 \times \text{tCO}_2.$$

Data analysis

The raw data were fed into an excel database and imported to SPSS IBM software. Descriptive statistics was used to calculate mean height, diameter at breast height (DBH) and basal girth of trees and shrubs. Significant differences within the quadrats were examined using one-way ANOVA followed by Duncans Multiple Range Test (DMRT). All statistical analysis was done in a 95% confidence interval.

Results

Growth and biomass from MFA

The results revealed significant differences for biomass and carbon stock in different trees of MFA ($P < 0.001$). Among the tree species in MFA, *Melia dubia* recorded the highest mean height and DBH (8.87 m and 12.43 cm respectively), followed by *Neolamarckia cadamba* (7.77 m and 12.80 cm respectively). The highest mean basal girth was recorded for *Madhuca latifolia* (39.70 cm), followed by *Syzygium cumini* (38.05), and the lowest in *Justicia adhatoda* (5.84 cm). Significantly higher biomass was recorded in five species, viz. *N. cadamba* (63.09 ± 4.87 kg tree^{-1}), *M. dubia* (54.43 ± 3.77 kg tree^{-1}), *Lagerstroemia parviflora* (36.39 ± 2.89 kg tree^{-1}) and *Dalbergia latifolia* (27.73 ± 2.61 kg tree^{-1}), whereas insignificant differences were observed in the remaining species ($P < 0.001$). The lowest biomass was recorded in *Justicia adhatoda* (0.23 ± 0.00), *Jatropha curcas* (0.34 ± 0.11 kg tree^{-1}), *Annona muricata* (0.44 ± 0.05 kg tree^{-1}) and *Citrus limon* (0.54 ± 0.07 kg tree^{-1}; Table 1).

Vegetation carbon stock

Among the high-value timber species, *Dalbergia latifolia* (11.31 and 2.94 kg tree^{-1} respectively) recorded the highest aboveground and belowground carbon stock, and all the three species, viz. *Santalum album* (1.17 and 0.30 kg tree^{-1} respectively), *Pterocarpus santalinus* (4.17 and 1.09 kg tree^{-1} respectively) and *D. latifolia* recorded significant differences in carbon stock. *L. parviflora* recorded the highest carbon stock (15.83; 4.12 kg tree^{-1}) and varied significantly along with *Gmelina arborea* in the timber species (Table 1). Within the plywood circle, *M. dubia* and *N. cadamba* varied significantly with carbon stock of 22.76 and 26.98 kg tree^{-1} aboveground and 5.92 and 7.01 kg tree^{-1} belowground respectively, whereas the other two species, viz. *Toona ciliata* and *Acrocarpus fraxinifolius* recorded insignificant differences. Significantly, the highest aboveground and belowground carbon stock was observed in *Terminalia arjuna* (4.56 and 1.19 kg tree^{-1} respectively) while the other three species (*Annona muricata*, *Aegle marmelos* and *Justicia adhatoda*) in the medicinal species recorded insignificant differences. Among the

Table 1. Biometric data, biomass and carbon stock (above- and belowground) in different species of multifunctional agroforestry

Common name	Scientific name	Mean height (m)	Mean diameter at breast height (DBH; cm)	Mean basal girth (cm)	Average above ground biomass (kg tree^{-1})	Average carbon stock (kg tree^{-1})		Carbon sequestration rate (kg tree^{-1} year^{-1})
						AGB–C	BGB–C	
High–value circle								
Sandal	*Santalum album*	2.50	3.93	–	$2.77^{a} \pm 0.35$	$1.17^{a} \pm 0.15$	$0.30^{a} \pm 0.03$	0.37
Red sanders	*Pterocarpus santalinus*	4.26	6.02	–	$10.26^{bc} \pm 0.83$	$4.17^{b} \pm 0.34$	$1.09^{b} \pm 0.08$	1.31
Rose wood	*Dalbergia latifolia*	6.09	8.40	–	$27.73^{f} \pm 2.61$	$11.31^{c} \pm 1.06$	$2.94^{c} \pm 0.28$	3.56
Timber circle								
Teak	*Tectona grandis*	5.57	9.15	–	$24.18^{ef} \pm 1.58$	$9.08^{b} \pm 0.59$	$2.36^{b} \pm 0.15$	2.84
Mahogany	*Sweitenia macrophylla*	6.08	9.01	–	$23.39^{ef} \pm 1.00$	$9.48^{b} \pm 0.41$	$2.47^{b} \pm 0.11$	2.99
Ben teak	*Lagerstroemia parviflora*	7.38	10.37	–	$36.39^{g} \pm 2.89$	$15.83^{c} \pm 1.26$	$4.12^{c} \pm 0.32$	4.99
White teak	*Gmelina arborea*	4.68	8.04	–	$14.19^{cd} \pm 2.36$	$6.37^{a} \pm 1.06$	$1.66^{a} \pm 0.28$	2.01
Plywood circle								
Malabar neem	*Melia dubia*	8.87	12.43	–	$54.43^{h} \pm 3.77$	$22.76^{b} \pm 1.58$	$5.92^{b} \pm 0.41$	7.17
Kadam	*Neolamarckia cadamba*	7.77	12.80	–	$63.09^{i} \pm 4.87$	$26.98^{c} \pm 2.09$	$7.01^{c} \pm 0.54$	8.50
Toon	*Toona ciliata*	5.62	7.01	–	$10.34^{bc} \pm 1.12$	$4.47^{a} \pm 0.45$	$1.16^{a} \pm 0.12$	1.41
Red cedar	*Acrocarpus fraxinifolius*	6.61	7.03	–	$17.61^{de} \pm 1.31$	$8.06^{a} \pm 0.60$	$2.09^{a} \pm 0.16$	2.54
Medicinal circle								
Soursop	*Annona muricata*	1.04	–	10.19	$0.44^{a} \pm 0.05$	$0.20^{a} \pm 0.02$	$0.05^{a} \pm 0.00$	0.06
Bael	*Aegle marmelos*	3.26	–	19.65	$2.48^{a} \pm 0.45$	$1.06^{a} \pm 0.19$	$0.28^{a} \pm 0.05$	0.34
Arjun tree	*Terminalia arjuna*	2.85	–	21.84	$11.39^{bcd} \pm 2.68$	$4.56^{b} \pm 1.07$	$1.19^{b} \pm 0.28$	1.44
Adhatoda	*Justicia adhatoda*	1.12	–	5.84	$0.23^{a} \pm 0.00$	$0.09^{a} \pm 0.00$	$0.02^{a} \pm 0.00$	0.02
Fruits circle								
Guava	*Psidium guajava*	2.45	–	17.30	$6.34^{ab} \pm 0.42$	$2.60^{b} \pm 0.17$	$0.68^{b} \pm 0.04$	0.82
Lemon	*Citrus limon*	1.01	–	12.02	$0.54^{a} \pm 0.07$	$0.24^{a} \pm 0.03$	$0.06^{a} \pm 0.00$	0.07
Sugar apple	*Annona squamosa*	2.49	–	15.62	$1.08^{a} \pm 0.12$	$0.47^{a} \pm 0.05$	$0.12^{a} \pm 0.01$	0.15
Jamun	*Syzygium cumini*	2.56	–	38.05	$11.17^{bcd} \pm 0.90$	$4.89^{c} \pm 0.39$	$1.27^{c} \pm 0.10$	1.54
Moringa circle								
Drum stick	*Moringa oleifera*	4.57	12.11	–	$23.36^{ef} \pm 1.35$	8.49 ± 0.49	2.21 ± 0.13	2.68
Border								
Oil nut tree	*Calophyllum inophyllum*	3.45	–	21.74	$5.24^{ab} \pm 0.50$	$2.23^{c} \pm 0.21$	$0.58^{c} \pm 0.06$	0.70
Mahua	*Madhuca latifolia*	2.32	–	39.70	$6.73^{ab} \pm 1.00$	$2.75^{c} \pm 0.42$	$0.72^{c} \pm 0.10$	0.87
Karanj	*Pungamia pinnata*	1.80	–	34.25	$5.06^{ab} \pm 0.44$	$2.06^{c} \pm 0.18$	$0.54^{c} \pm 0.05$	0.65
Paradise tree	*Simarouba glauca*	2.10	–	29.38	$2.59^{a} \pm 0.35$	$1.11^{b} \pm 0.15$	$0.29^{b} \pm 0.03$	0.35
Physic nut	*Jatropha curcas*	1.20	–	18.83	$0.34^{a} \pm 0.11$	$0.12^{a} \pm 0.04$	$0.03^{a} \pm 0.00$	0.04
Mean								1.90

According to Duncans multiple range test (DMRT), average values with different superscript in a column are significantly different. Biomass and carbon stock values are expressed as mean ± SE ($P < 0.001$).

Table 2. Total carbon sequestration in different quadrats of multifunctional agroforestry

Quadrat	Scientific name	Tree density	Total carbon stock (kg quadrat^{-1})	CO_{2e} (kg quadrat^{-1})
I	*S. album*	12	19.18^{ab}	70.39
	T. grandis	12	137.32^{d}	503.96
	M. dubia	11	286.97^{e}	1053.18
	A. muricata	11	2.78^{a}	10.20
	P. guajava	10	36.09^{b}	132.45
	M. oleifera	4	32.86^{c}	120.59
Total		60	515.2	1890.78
II	*P. santalinus*	12	42.02^{a}	154.21
	S. macrophylla	12	143.46^{b}	526.49
	N. cadamba	11	408.01^{c}	1497.39
	A. marmelos	11	14.76^{a}	54.17
	C. lemon	6	1.80^{a}	6.60
	M. oleifera	4	40.86^{b}	149.96
Total		56	650.91	2388.84
III	*L. parviflora*	12	259.25^{d}	951.45
	T. ciliata	11	56.34^{b}	206.77
	T. arjuna	11	63.25^{b}	232.13
	A. squamosa	10	5.91^{a}	21.69
	M. oleifera	4	49.93^{c}	183.24
Total		48	434.68	1595.28
IV	*D. latifolia*	12	185.26^{e}	679.90
	G. arborea	12	96.37^{bc}	353.68
	A. fraxinifolius	11	111.73^{cd}	410.05
	J. adhatoda	11	1.34^{a}	4.92
	S. cumini	10	61.63^{b}	226.18
	M. oleifera	4	47.60^{de}	175.57
Total		60	503.93	1850.30
Border	*P. pinnata*	10	25.81^{c}	94.72
	C. inophyllum	5	14.02^{c}	51.45
	M. latifolia	5	17.35^{c}	63.67
	S. glauca	8	11.13^{b}	40.85
	J. curcas	96	46.08^{a}	169.11
Total		124	114.39	1540.71
Total (0.75 acre)		348	2219.11 (2.23 tonnes)	9265.91 (9.23 tonnes)
Carbon revenue (Carbon price: US$ 4 per tCO_2)				US$ 36.92

According to DMRT, the value of total carbon stock followed by different alphabets in superscript is significantly different within a particular circle of MFA.

fruit trees, *S. cumini* (4.89 and 1.27 kg tree^{-1}) and *Psidium guajava* (2.60 and 0.68 kg tree^{-1}) recorded significantly highest carbon stock (above- and belowground), and insignificantly lowest carbon stock was observed in *Citrus limon* (0.24 and 0.06 kg tree^{-1} respectively) and *Annona squamosa* (0.47 and 0.12 kg tree^{-1} respectively). In the border trees of MFA, highest carbon stock was recorded in *Madhuca latifolia* (2.75 and 0.72 kg tree^{-1}) but it was insignificant ($P < 0.001$). However, significant differences were observed in *Simarouba glauca* (1.11; 0.29 kg tree^{-1}) and *Jatropha curcas* (0.12; 0.03 kg tree^{-1}). The rate of carbon sequestration ranged from 0.02 (*Justicia adhatoda*) to 8.50 kg tree^{-1} year^{-1} (*N. cadamba*; Table 1).

Total carbon sequestration

A total of 2.23 tonnes (2219.11 kg) of carbon was sequestered from MFA of 0.75 acres comprising 235 trees and shrubs and 124 TBOs. Among the four quadrats, the highest total carbon sequestration (TCS) was from quadrat II (650.91 kg quadrat^{-1}) followed by quadrat I (515.20 kg quadrat^{-1}) with tree density of 56 and 60 respectively. The maximum contribution of the highest TCS was from *N. cadamba* (408.01 kg quadrat^{-1}) and *S. macrophylla* (143.46 kg quadrat^{-1}). Significantly, the highest TCS was recorded in *M. dubia* (286.97 kg quadrat^{-1}) followed by *T. grandis*, *P. guajava* and *Moringa oleifera* in quadrat I. The lowest TCS was from quadrat III (434.68 kg quadrat^{-1}) with tree density of 48. *L. parviflora* sequestered more carbon (259.25 kg quadrat^{-1}) and varied significantly along with *A. squamosa* (5.91 kg quadrat^{-1}) and *M. oleifera* (49.93 kg quadrat^{-1}), whereas *T. ciliata* and *T. arjuna* differed insignificantly. In the border of four quadrats with a tree density of 124, the lowest TCS recorded was 114.39 kg (Table 2). *J. curcas* (46.08 kg) and *S. glauca* (11.13 kg) differed significantly, while the remaining three species, viz. *C. inophyllum*, *M. latifolia* and *P. pinnata* recorded insignificant differences

Table 3. One-way ANOVA for total carbon sequestration among different quadrats of MFA

Total carbon stock	Sum of squares	*Df*	Mean square	*F*	*P*-value
Quadrat I	5872.739	5	1174.548	144.970	<0.001
Quadrat II	8251.716	5	1650.343	78.442	
Quadrat III	2526.687	4	631.672	43.419	
Quadrat IV	1333.848	5	266.770	24.209	
Border	29.036	4	7.259	14.107	

Table 4. Change in soil organic carbon at different depths of MFA

Quadrat	Soil depth (cm)	Initial soil carbon stock		Final soil carbon stock		Change in soil carbon stock over four years		CO_{2e} (Mg quadrat^{-1})	Soil C sequestration rate (Mg ha^{-1} year^{-1})
		Mg ha^{-1}	Mg quadrat^{-1}	Mg ha^{-1}	Mg quadrat^{-1}	Mg ha^{-1}	Mg quadrat^{-1}		
I	0–20	21.68 ± 1.83	7.80 ± 0.65^{abc}	24.64 ± 1.77	8.87 ± 0.64^{a}	2.96	1.07	10.89	0.74
	20–40	23.1 ± 1.41	8.31 ± 51^{abc}	25.87 ± 1.58	9.31 ± 0.57^{ab}	2.77	1.00		0.69
	40–60	20.83 ± 0.68	7.49 ± 0.24^{ab}	23.30 ± 0.89	8.39 ± 0.32^{ab}	2.47	0.90		0.62
Total		65.61	23.6	73.81	26.57	8.20	2.97		–
II	0–20	30.48 ± 2.66	10.97 ± 0.96^{d}	34.08 ± 3.04	12.27 ± 1.09^{c}	3.60	1.3	11.08	0.90
	20–40	23.48 ± 0.71	8.45 ± 0.22^{abc}	26.07 ± 1.01	9.39 ± 0.36^{ab}	2.59	0.94		0.65
	40–60	20.73 ± 0.71	7.46 ± 0.25^{ab}	22.89 ± 0.87	8.24 ± 0.32^{a}	2.16	0.78		0.54
Total		74.69	26.88	83.04	29.9	8.35	3.02		–
III	0–20	21.01 ± 0.43	7.57 ± 0.27^{ab}	23.30 ± 0.57	8.39 ± 0.21^{a}	2.29	0.82	8.51	0.57
	20–40	21.30 ± 0.91	7.67 ± 0.33^{ab}	23.40 ± 0.94	8.42 ± 0.33^{a}	2.10	0.75		0.52
	40–60	19.88 ± 0.33	7.16 ± 0.12^{a}	21.97 ± 0.27	7.91 ± 0.09^{a}	2.09	0.75		0.52
Total		62.19	22.4	68.67	16.72	6.48	2.32		–
IV	0–20	31.05 ± 1.56	11.18 ± 0.56^{d}	34.08 ± 1.78	12.27 ± 0.64^{c}	3.03	1.09	11.89	0.76
	20–40	24.80 ± 0.62	8.93 ± 0.22^{bc}	28.03 ± 0.17	10.09 ± 0.06^{b}	3.23	1.16		0.81
	40–60	25.47 ± 0.84	9.17 ± 0.30^{c}	28.23 ± 0.89	10.16 ± 0.32^{b}	2.76	0.99		0.69
Total		81.32	29.28	90.34	32.52	9.02	3.24		–
Total change in SOC stock						32.05	11.55	42.37	–
Marketable carbon revenue (US$ 4 per tCO_2)								$169.48	–
Average Soil C sequestration rate									0.53

Alphabets with same letters in superscript (a, b, c, d) are insignificant. Data expressed as mean ± SE ($P < 0.001$).

in the border trees of MFA (Table 2). One-way ANOVA showed significant differences among the four quadrats and border of MFA ($P < 0.001$) (Table 3).

Soil organic carbon

The change in SOC stock was higher in 0–20 cm depth in all quadrats and the total change in SOC stock was 32.05 Mg ha^{-1} and 11.55 Mg quadrat^{-1} for MFA alone. However, insignificant differences were seen in different soil depths (0–60 cm) in all quadrats ($P < 0.001$). Higher SOC stock was observed in quadrat IV and II quadrats (32.52 and 29.9 Mg quadrat^{-1} respectively) and the same trend was noted for CO_{2e}. The mean soil carbon sequestration rate was 0.53 Mg ha^{-1} year^{-1} (Table 4).

Discussion

Biomass and carbon stock of MFA

Carbon stock from agroforestry systems has been studied by various national and international organizations from all over the world[3,24]. The biomass from MFA ranged from 0.23 (*J. adhatoda*) to 63.09 kg tree^{-1} (*N. cadamba*). Ajit *et al.*[24] have reported biomass in tree components of different agroforestry systems to be ranging from 0.58 to 48.50 DM Mg ha^{-1}. Significant differences in biomass and carbon stock (AGB-C and BGB-C) were noticed in the high-value timber circle for three species, viz. *S. album*, *P. santalinus* and *D. latifolia* (Table 1). AGB values for *P. santalinus* and *S. album* were reported by Singh[25] and Tamilselvan *et al.*[26] in forest plantations. These species have high WSG and density as well and help in sequestering more carbon in the long term. However, incorporation of high-value species for carbon storage needs to be explored especially in agroforestry systems. In the timber circle, *L. parviflora* recorded the highest biomass and carbon stock (36.39 and 15.83 kg tree^{-1} respectively). This is due to the maximum height and diameter (7.38 m and 10.57 cm respectively) of the *L. parviflora* when compared to other species. The carbon stock is highly influenced by tree density and diameter, and may vary from one farm to another[17]. Several researchers have reported DBH as a predictor for estimating biomass in agroforestry

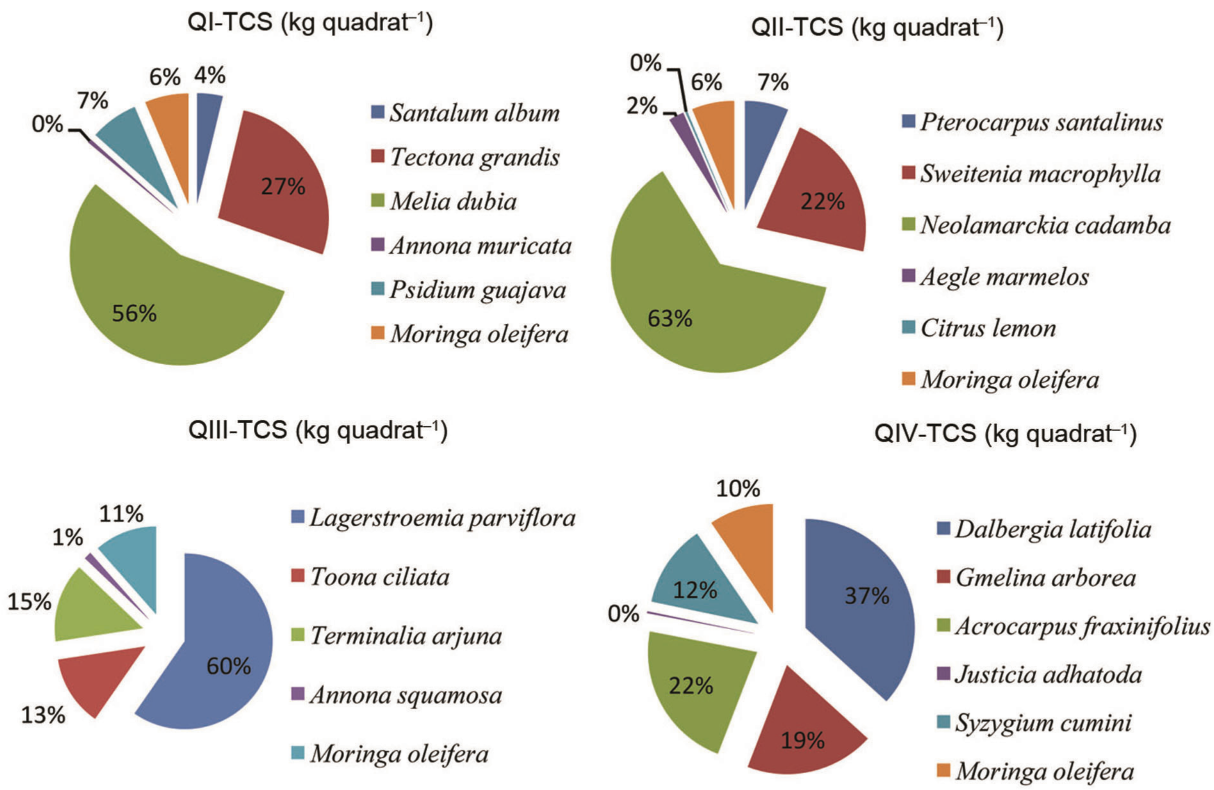

Figure 2. Contribution of different species to total carbon sequestered within the quadrats of MFA.

species[27–29]. In the plywood circle, a similar trend was observed for *N. cadmba* (7.77 m height, 12.80 cm DBH and biomass 63.09 kg tree^{-1}) and *M. dubia* (8.87 m height, 12.43 cm DBH and biomass 54.43 kg tree^{-1}), whereas Marak and Khare[30] recorded a biomass of 5.93 tonne tree^{-1} in *N. cadamba*. The fruit circle followed the order of biomass and carbon stock: *S. cumini* > *P. guajava* > *A. squamosa* > *C. limon* (Table 1). Similarly, Nimbalkar *et al.*[31] also reported carbon stock from a smallholder fruit-based agroforestry system in Rajasthan, India.

Carbon sequestration and valuation from MFA

Farmers' decisions in selecting tree species, the number of trees and farm management practices play an important role in influencing carbon sequestration from smallholder agroforestry systems[23]. In the present study, the maximum contribution of carbon sequestration was from *M. dubia* (56%) followed by *T. grandis* (27%) in quadrat I (Figure 2). A six-year *M. dubia*-based agrisilvicultural system recorded carbon sequestration of 98.9–137.5 tonne ha^{-1}, as reported by Chandana *et al.*[32]. In quadrat II, the maximum contribution was from *N. cadamba* (63%) and 60% from *L. parviflora* in quadrat III. The highest contribution to carbon sequestration was from *D. latifolia* (37%) followed by *A. fraxinifolius* (22%) in quadrat IV respectively (Figure 2). The maximum contribution of tree species for carbon sequestration can be attributed to tree density and DBH which allows more fixation of carbon dioxide in woody tissues[33]. The highest CO_{2e} was from quadrat II (2388.84 kg quadrat^{-1}), because this quadrat contains fast-growing multipurpose tree species, *N. cadamba*. The mean carbon sequestration rate from MFA was 1.90 (kg tree^{-1} year^{-1}; Table 1) against the country's carbon sequestration potential from farmers' fields of 0.21 Mg C ha^{-1} year^{-1}, as reported by Ajit *et al.*[24]. The maximum soil CO_{2e} was from quadrat IV (11.89 Mg C quadrat^{-1}; Table 4), which can be attributed to intercrops, viz. Guinea grass and *Desmanthus* adding carbon to the soil through litter and root turnover. Other factors that influence SOC are temperature, rainfall, decay of roots, litterfall and prevailing microclimatic condition. Soil carbon sequestration rate in the present study was 0.53 Mg C ha^{-1} year^{-1} (Table 4). The same trend was reported by Ajit *et al.*[24] in different agroforestry systems of India, ranging from 0.003 to 0.51 Mg C ha^{-1} year^{-1}.

In order to encourage smallholders to practice agroforestry in the short and long term, an initiative in the REDD^{+} target has been taken mainly to promote sustainable land-use systems and carbon conservation over a long period of time. This could be an attractive option to improve the status of smallholder farmers, especially in low-income countries[34]. In line with this, the present study has valued the total carbon revenue of MFA as US$ 206.40 respectively (US$ 36.92 from vegetation and US$ 169.48 from soil) (Tables 2 and 4).

Conclusion

Holistically, smallholder MFA of 0.75 acres is able to sequester 2.23 tonne and 11.5 Mg C from vegetation and soil respectively. Among all the quadrats, quadrat II sequestered more carbon (AGB-C and BGB-C) due to the presence of fast-growing tree species, *N. cadamba*, while quadrat IV sequestered more carbon in the soil, which can be attributed to fodder species. Furthermore, the carbon revenue (US$ 206.40) generated could act as an incentive in addition to other profits from agroforestry. However, carbon market and payment is still a debatable issue, i.e. should farmers be paid for carbon storage in standing biomass. Therefore, the results of this study could be useful to policymakers while taking into account smallholder farmers' interests and profitability and also to achieve the $REDD^+$ initiative, mainly in low-income and developing countries.

Conflict of interest: The authors declare no conflict of interest.

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