Carbon sequestration potential of mango orchards in India

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Estimates of carbon stocks and stock changes in fruit orchards are necessary under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. In this direction we estimated the carbon stocks in cultivated mango orchards in India using an exclusive allometric equation developed for estimation of tree biomass of grafted mangoes. Extensive tree, litter, weed and soil samples were collected for estimation of carbon pools by grouping mango areas based on similarity of tree canopy, climate, and dominance of mango varieties grown in these regions. The carbon held in these pools was then compiled and national-level carbon storage in cultivated mango orchards was computed by multiplying with the area occupied by mango in these regions. The country as a whole has sequestered 285.005 mt of carbon in its mango orchards. This is, however, very low compared to polyembrionic mango trees grown from seeds in the wild.

Keywords: Allometric equation, carbon sequestration, mango orchards, tree biomass.

AMONG the terrestrial ecosystems, forest ecosystems have been identified as the largest land carbon sink and account for more than half of the carbon stored in terrestrial ecosystems[1,2]. The Indian forests sequester about 5.3–6.7 Pg C (refs 3, 4). However, during first few years of establishment both forests and orchards may sequester similar amounts of carbon[5]. Researchers have studied the contribution of orchards to carbon cycle like C storage[6], root respiration[7–9] and net CO_2 flux[10]. Compared to forest stands, the potential for C credits based on standing biomass for orchards growing in the same climatic zone is limited. Most of the available information on orchards is from temperate regions, particularly from apple and citrus orchards. For example, it is reported[5] that the New Zealand orchards (25 years old) roughly sequester about 70 tonne C ha^{-1}, but in the same climatic region *Pinus radiata* forest stands sequester about 300–500 tonne carbon ha^{-1}. There are limitations in such comparisons as different criteria were followed in both estimations. For example, in orchards the tree biomass was only considered ignoring indirect C emissions associated with orchard management practices which involve periodic input of organic materials and the decomposition rate of soil organic matter[11]. Published work on carbon sequestration in orchards mainly ignored the role of litter fall like flowers, fruits, leaves, pruned biomass, microbial respiration and rhizo deposition in the overall C balance of an orchard. Further partitioning of C in orchards to different organs of the fruit trees depends on genotype, tree age, planting density, fruit yield, canopy management and input additions[12].

One of the options for reducing the rise of greenhouse gas (GHG) concentration in the atmosphere and thus possible climate change is to increase the amount of C removed by and stored in perennial plants. But due to large-scale industrialization and increased population, the forest area is declining. However, the perennial fruit orchards area is on the increase[13]. Nevertheless, orchards do have a potential similar to forests, but on a lower scale because of indirect C emissions associated with orchard management practices[14–17]. It has been shown that by practising conservation horticulture we can attain C sequestration levels in mango orchards similar to forest ecosystem[18]. An estimate of C sequestration potential of fruit orchards in India is therefore essential for any strategic planning, offsetting GHG emissions and for trading carbon.

Mango is the major fruit crop of India and it is evergreen. It is grown in seasonally moist tropical climate having a distinct dry and wet season. There is a strong seasonality of photosynthetically active radiation usually being much larger in late wet season than in the dry season.

Two types of mango population occur in India – the wild poly embryonic mango and the cultivated grafted mango. Estimates of the population and area occupied by wild poly embryonic mango are not available, but surely must be a sizable area as India is the origin of mangoes. Cultivated mango occupies an area of nearly 2,263,000 ha and has great potential for carbon sequestration[13]. The area is further expected to increase given the importance gained by horticulture sector in government policies in recent years. It is essential to have a national database on the C sequestration by cultivated mangoes in India. This communication reports estimates of C sequestration in mango orchards of India.

Mango is grown in every state of India and the area (2,263,000 ha) varies extensively with large localized

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Table 1. Grouping of states for sampling purpose

Group no.	State	Popular varieties
1	Bihar, Chattisgarh, Jharkhand, Madhya Pradesh	Jardalu, Langra, Chaunsa, Gulaab Khaas
2	Haryana, Punjab, Rajasthan, Uttar Pradesh,	Dusheri, Langra, Chaunsa
3	Jammu and Kashmir, Himachal Pradesh, Uttarakhand,	Chaunsa, Dusheri, Langra
4	Karnataka	Totapuri, Raspuri, Badami
5	Andhra Pradesh, Telangana	Banganapalli, Totapuri
6	Tamil Nadu	Neelam, Mulgoba
7	Kerala, Goa, Gujarat, Maharashtra, Others	Alphonso, Kesar
8	West Bengal, Odisha and Tripura	Himsagar, Amrapali
9	Andaman and Nicobar Islands, Assam, Arunachal, Mizoram, Nagaland	Mixed varieties
10	Others	Mixed varieties

pockets located in different regions and has gained variety-wise recognition like Dusheri, Langra and Chaunsa in the Indogangetic plain, Alphonso in Konkan region, Totapuri, Raspuri and Badami in Karnataka, Banganapalli in Andhra Pradesh and Telangana, Kesar in Gujarat, Himsagar in West Bengal, Neelam and Mulgoba in Tamil Nadu, etc. (Table 4) Hence it is a practical difficulty to sample over this large area. Further ecological grouping is not possible as the mango database is available only on political boundary basis. Hence for sampling purpose, the mango-growing states were grouped based on similarity of tree canopy, climate and dominance of mango variety grown in these regions (Table 1). Extensive survey was conducted in these regions for recording allometric data. From each region randomly 100–350 economically bearing orchards (mostly tree age of about 25 years) were sampled to obtain a fairly representative sample of the orchards from these states.

As mentioned above, allometric data were collected from randomly selected trees from each of the regions listed in Table 1. All the orchards selected contained only grafted trees and hence we followed the allometric equation developed by Ganeshamurthy *et al.*[19] for grafted mangoes for estimating the above ground and below ground tree biomass as there was no scope for recording the diameter at breast height (DBH), a parameter necessary for using general allometric equation for estimating tree biomass. The measurement included the number of primary branches and girth of the primary branches. Briefly, the allometric equation was developed through destructive sampling of 74 mango trees covering the age group from 3 to 85 years. Allometric parameters such as number of primary and secondary branches, girth of primary and secondary branches, tree height, tree volume, basal diameter and diameter below graft union (DBGU) were measured on 74 randomly selected mango trees of different age groups: 3, 5, 8, 10, 12, 15, 16, 20, 45 and 85 years. Stem diameter (below graft union) was measured with a diameter tape. The height of the tree and diameter of the crown were measured with a Spiegel relaskop.

Different statistical models were used to estimate tree biomass like logistic model, Gompertz model and power model. As all these three models are a class of nonlinear regression model, as the derivatives of Y_t with respect to unknown parameters are functions of either of them, suitable nonlinear estimation procedure was followed for parameter estimation[20,21]. SAS codes were developed to fit these nonlinear regression models. Based on the best fit, the power model was used for the estimation of tree biomass.

The power model is represented by the following equation

$$Y_t = aX_t^{\,b} + \varepsilon_t,$$

Y_t is the tth trees ABG (above ground biomass), X_t the tth trees observations on PBG (primary branch girth) × NPB (No. of primary branches), ε_t the error terms corresponding to difference between observed and expected tree ABG of tth tree. For below ground biomass estimation, we followed the ratio of 1 : 0.29 as suggested by Ganeshamurthy *et al.*[14].

Mature leaves were collected from 20 random trees from each sampling area (Table 2) for estimation of carbon content. These samples were pooled, washed and dried at 65°C in a hot-air oven till constant weight. The samples were then powdered for C estimation.

Similarly, samples of twigs representing tertiary branches and other smaller branches were also selected and processed for C estimation.

The bark and wood samples were collected from selected trees using a tree drill and processed for C estimation.

Representative area in such orchards where the litter was left unattended was sampled for collection of litter and weed biomass, and the samples were dried and processed for C estimation. Wherever the sampling was not possible, data were collected from published works from these states[22,23].

The C content of these plant samples was estimated using a CHNS analyzer (Elementar) and expressed as per cent carbon in the sample.

The litter and weed biomass collected from these orchards were processed and analysed for their C content using a CHNS analyser (Elementar) and expressed as per cent C in the sample.

Soil carbon stock is the most difficult pool to obtain representative data. Practically it was difficult to arrive at a state-wise average soil organic carbon (SOC) as no

Table 2. Mean allometric parameters and tree carbon sequestered in mango orchards of India

States/ Union Territory (UT)	Number of primary branches*	Mean girth of primary branches (cm)*	AGB (kg $tree^{-1}$)	AGB carbon (kg $tree^{-1}$)	BGB (kg $tree^{-1}$)	BGB carbon (kg $tree^{-1}$)	Total carbon (kg $tree^{-1}$)	Total carbon (tonne ha^{-1})*
Bihar	3.6	157.1	1554.0	699.3	468.7	225.0	924.3	92.43
Chhatisgarh	3.6	157.1	1554.0	699.3	468.7	225.0	924.3	92.43
Haryana	3.5	156.20	1534.5	690.5	462.8	222.10	912.7	91.27
Himachal Pradesh	3.5	105.30	952.4	571.4	287.2	176.80	748.2	74.82
Jammu and Kashmir	3.5	105.30	952.4	571.4	287.2	176.80	748.2	74.82
Jharkhand	3.6	157.1	1554.0	699.3	468.7	225.0	924.3	92.43
Madhya Pradesh	3.6	157.1	1554.0	699.3	468.7	225.0	924.3	92.43
Punjab	3.5	156.20	1534.5	690.5	462.8	222.10	912.7	91.27
Rajasthan	3.5	156.20	1534.5	690.5	462.8	222.10	912.7	91.27
Uttarakhand	3.5	105.30	952.4	571.4	287.2	176.80	748.2	74.82
Uttar Pradesh	3.5	156.20	1534.5	690.5	462.8	222.10	912.7	91.27
Andhra Pradesh	3.0	164.0	1571.5	707.2	474.0	227.5	934.7	93.47
Karnataka	3.5	105.30	952.4	571.4	287.2	176.80	748.2	74.82
Kerala	3.6	81.0	776.9	349.6	234.3	112.5	446.2	46.21
Tamil Nadu	3.5	81.8	777.9	466.8	234.6	144.4	611.2	61.12
Telangana	3.0	164.0	1571.5	707.2	474.0	227.5	934.7	93.47
Goa	3.6	81.0	776.9	349.6	234.3	112.5	446.2	46.21
Gujarat	3.6	81.0	776.9	349.6	234.3	112.5	446.2	46.21
Maharashtra	3.6	81.0	776.9	349.6	234.3	112.5	446.2	46.21
Andaman and Nicobar and LD	3.5	105.30	952.4	571.4	287.2	176.80	748.2	74.82
Assam	3.5	105.30	952.4	571.4	287.2	176.80	748.2	74.82
Arunachal Pradesh	3.5	105.30	952.4	571.4	287.2	176.80	748.2	74.82
Mizoram	3.5	105.30	952.4	571.4	287.2	176.80	748.2	74.82
Nagaland	3.5	105.30	952.4	571.4	287.2	176.80	748.2	74.82
Odisha	3.6	93.5	908.0	408.6	273.9	168.5	577.1	57.71
West Bengal	3.6	93.5	908.0	408.6	273.9	168.5	577.1	57.71
Tripura	3.6	93.5	908.0	408.6	273.9	168.5	577.1	57.71
Others	3.6	81.0	776.9	349.6	234.3	112.5	446.2	46.21
Mean	3.507143	117.7214	1123.393	555.6	338.8071	180.25	733.025	73.58643

*Mean of 100 trees. AGB, Above ground biomass; BGB, Below ground biomass.

single publication has done any such exercise in India to obtain a political boundary-based average SOC. However, the Forest Survey of India (FSI)[24] has generated this information and the latest data were published in 2017. Since orchard ecosystem is closer to a forest ecosystem than an agro-ecosystem, and the sampled orchards are in the age group of about 25 years, we utilized the data for state average values of SOC. Briefly, the method used by FSI for collecting data on SOC is as follows: a representative site was selected from different regions of the state. While collecting soil sample, the floor was first swept and then a pit was dug and a composite sample was collected and analysed for organic C content and used for the calculation of SOC in the soil profile.

Carbon storage from mango trees was estimated based on dry matter and C content of the tree parts. The mean number of primary branches in orchard mango trees varied from 3.0 to 3.60 in different states. The average number of primary branches observed across the country was 3.507 (Table 2). The girth of primary branches differed in different state orchards depending upon climate and variety. The overall mean primary girth of mango trees varied from 81 to 164 cm. The lowest girth (81 cm) was recorded in western India representing Konkan region, Kerala and Gujarat. While the maximum tree primary branch girth (64 cm) was recorded in Andhra Pradesh and Telangana region followed by Madhya Pradesh, Bihar, Jharkhand and Chhattisgarh region. This shows that there is a significant difference in the orchard mango tree robustness in different regions of the country.

Utilizing these two tree parameters the above ground biomass of mango trees was estimated following the allometric equation developed for grafted mangoes by Ganeshamurthy *et al.*[14]. The above ground tree biomass in different states ranged from 776.9 to 1574 kg $tree^{-1}$. Averaged over different states, the above ground tree biomass was 1123.39 kg $tree^{-1}$. On per tree basis, the above ground tree biomass was more in groups 1, 2 and 5 representing major mango belts of the Indo-gangetic plain and Andhara Pradesh–Telangana region. The least was recorded in Konkan region, Kerala, Bay Islands and NEH region.

The above ground biomass was far less than that of ungrafted polyembryonic mango trees grown wild in forests and in isolated places in farmers' fields and avenues, which have tree diameter as large as 500 cm (refs 18, 19).

Table 3. Litter and weed biomass carbon in mango orchards of India

States/UT	Weed biomass (kg/ha)	Weed carbon (kg/ha)	Litter biomass (kg/ha)	Litter carbon (kg/ha)	Total carbon content (tonne ha^{-1})
Bihar	1360	632.4	1690	772.33	1.40473
Chhatisgarh	1820	846.3	1460	667.22	1.51352
Haryana	1210	562.65	1380	630.66	1.19331
Himachal Pradesh	1380	641.7	1380	630.66	1.27236
Jammu and Kashmir	1400	651	1380	630.66	1.28166
Jharkhand	2040	948.6	1460	667.22	1.61582
Madhya Pradesh	2320	1078.8	1460	667.22	1.74602
Punjab	1100	511.5	1380	630.66	1.14216
Rajasthan	880	409.2	1380	630.66	1.03986
Uttarakhand	1760	818.4	1460	667.22	1.48562
Uttar Pradesh	1850	860.25	1580	722.06	1.58231
Andhra Pradesh	2020	939.3	1540	703.78	1.64308
Karnataka	1960	911.4	1460	667.22	1.57862
Kerala	580	269.7	1304	595.93	0.86563
Tamil Nadu	2100	976.5	1460	667.22	1.64372
Telangana	1850	860.25	1540	703.78	1.56403
Goa	476	221.34	1304	595.93	0.81727
Gujarat	1460	678.9	1440	658.08	1.33698
Maharashtra	1780	827.7	1304	595.93	1.42363
Andaman and Nicobar & LD	2050	953.25	1304	595.93	1.54918
Assam	2200	1023	1304	595.93	1.61893
Arunachal Pradesh	2400	1116.0	1304	595.93	1.71193
Mizoram	2400	1116.0	1304	595.93	1.71193
Nagaland	2400	1116.0	1304	595.93	1.71193
Odisha	1800	837	1450	662.65	1.49965
West Bengal	2010	934.65	1450	662.65	1.5973
Tripura	2400	1116	1304	595.93	1.71193
Others	2000	930	1460	667.22	1.59722
Mean	1750.21	813.85	1412.36	645.45	1.46

Based on our experience at IIHR mean carbon content of weeds was assumed as 46.5% and litter carbon content as 45.7%.

Similarly, the below ground biomass was estimated following the root-to-shoot ratio of 0.29 recommended by Ganeshamurthy *et al.*[14]. The below ground biomass (Table 2) also followed a similar trend as above ground biomass. The tree root (below ground biomass) in different states ranged from 234.3 to 474 kg $tree^{-1}$. Averaged over different states, the tree root biomass was 338.8 kg $tree^{-1}$. On per tree basis, the tree root biomass was more in groups 1, 2 and 5 representing major mango belts of the Indo-Gangetic plain and Andhra Pradesh–Telangana region. The least was recorded in Konkan region, Kerala, Bay Islands and North East Hill (NEH) region.

Utilizing the mean C content of the above and below ground mango biomass, the total above ground and below ground C sequestered by grafted mangoes was estimated. The total C sequestered per tree across the country varied from 446.2 to 934.7 kg $tree^{-1}$. On all-India basis, grafted mangoes sequestered 733.03 kg C $tree^{-1}$. This is far below the values reported for polyembryonic wild mango trees[19], as the grafted mangoes are dwarfs, planted close and regularly canopy is managed to maintain short stature of the tree.

Weeds and litter represent the floor-level C sequestration. The annual weed biomass was estimated from the weed samples collected from sampled orchards in different states. For those states where sampling was not done, the data were obtained from other published works from the respective states. The weeds in mango orchards are mostly ephemerals in nature, seasonal and more during monsoon period. Due to tropical climate, weed biomass sometimes exceeds the litter biomass. It finally does enter into C cycle in the orchards contributing to SOC. Weed biomass varied from 476 kg ha^{-1} in Goa to as high as 2400 kg ha^{-1} in the NEH region. The mean weed biomass in mango orchards in the country as a whole was 1750.2 kg ha^{-1}. Orchards in NEH, Madhya Pradesh and Tamil Nadu had higher weed biomass and hence captured higher C followed by Jharkhand, Andhra Pradesh and Andaman and Nicobar Islands (Table 3). The differences are attributed to climate and the general management of mango orchards. This is reflected in the C capture through weeds in different regions.

The litter biomass in orchards varied from 1304 kg ha^{-1} in Goa to as high as 1690 kg ha^{-1} in Bihar followed by Uttar Pradesh, Andhra Pradesh and Telangana region. The mean litter biomass in mango orchards in the country as a whole was 1412.36 kg ha^{-1} (Table 3). The litter biomass depended more on the variety, tree growth and fruiting behaviour. The mango yields are generally better in the Indo-Gangetic belt than those of the Konkan region

Table 4. Soil C in mango orchards of India

State/UT	Soil carbon (tonne/ha)	Area (000 ha)	Total soil carbon stock (1000 tonnes)
Bihar	39.55	150.64	5957.812
Chhattisgarh	49.67	73.99	3675.083
Haryana	46.05	09.42	433.791
Himachal Pradesh	55.09	41.52	2287.337
Jammu and Kashmir	55.24	12.67	699.891
Jharkhand	43.29	52.24	2261.470
Madhya Pradesh	41.17	40.08	1650.094
Punjab	48.84	06.85	334.554
Rajasthan	26.21	05.00	131.050
Uttarakhand	59.91	35.93	2152.566
Uttar Pradesh	41.45	264.93	10981.350
Andhra Pradesh	42.09	332.97	14014.710
Karnataka	77.14	192.61	14857.940
Kerala	75.77	69.11	5236.465
Tamil Nadu	41.64	160.94	6701.542
Telangana	39.49	180.62	7132.684
Goa	52.42	4.77	250.0434
Gujarat	44.04	153.18	6746.047
Maharashtra	57.23	157.07	8989.116
Andaman and Nicobar & LD	101.12	0.05	5.056
Assam	39.98	5.58	223.088
Arunachal Pradesh	101.12	0.05	5.056
Mizoram	40.26	0.89	35.831
Nagaland	81.04	0.64	51.866
Odisha	46.50	199.3	9267.450
West Bengal	59.88	97.93	5864.048
Tripura	54.80	11.64	637.872
Others	42.00	6.98	293.160
Mean	53.67821	80.98571	3959.892

Total soil carbon stock from mango orchards in India = 110.877 mt.

and southern region. This is reflected in the litter biomass and carbon captured through litter.

As mentioned above, weed biomass exceeded litter biomass. The weeds are both dicot and monocot, and ephemerals in nature and are specific to the location. They are seasonal and more during monsoon period. With the tropical climate and mango being evergreen, the litter biomass could be less than the ephemeral weed biomass. The ephemeral weeds grow aggressively during monsoon season and produce biomass rapidly and can therefore surpass the quantity of litter from the evergreen mango. Hence the overall mean carbon credited from weed biomass was 813.85 kg ha^{-1}, as against the mean carbon credited by the litter, viz. 645.45 kg ha^{-1} (Table 3). It finally enters into C cycle in the orchards contributing to SOC.

The proportion of litter fraction in the total C sequestration is very low. Generally in the forests the floor C represents less than 10% of the total C sequestered[25]. This is highly variable in fruit orchards as it depends upon the management followed in different orchards. If weeding is practised regularly, the fraction of this C will be low. In the present study, this proportion ranged from 0.996% in the Konkan and western regions to 2.81 in Assam and Madhya Pradesh region, with a mean of 2.04% across the mango orchards in the country. This shows that there are regional differences in weed and litter biomass production and it depends mainly on tree growth, variety, bearing habit of the orchards and the management practices followed in these regions. Despite its modest contribution to total C, litter plays an important role in the C biogeochemical cycle as the interface between C in vegetation and soil.

The soil system attains a quasi-equilibrium stage after accumulation of dry matter and loss of SOC over time depending on land-use systems. Thus, SOC levels often show tooth-like cycles of accumulation and loss. After each change in land-use system, a period of constant management is required to reach a new quasi-equilibrium value (QEV). In this way, SOC is stabilized to a new QEV of the changed situation in terms of new land-use patterns, vegetation cover and management practices. The SOC tends to attain a QEV with varying duration of 500–1000 years in a forest system, 30–50 years in agricultural systems after forest cutting, 20–50 years under different agricultural systems and 30 years for horticultural system[16]. Ganeshamurthy[26] has shown that horticultural systems under these tropical land uses attain QEV in 25 years.

Indians have been cultivating mangoes for more than 4000 years. Emperor Akbar built the vast Lakhi Bagh

Table 5. Carbon pool compartment (tonne ha^{-1}) in mango orchards of India

State	AGB tree carbon	Litter carbon	Weed carbon	Total above ground carbon	Root carbon	Soil carbon	Total below ground carbon	Total carbon sequestered in orchards
Bihar	69.93	0.772	0.632	71.335	22.5	39.55	62.05	133.385
Chhattisgarh	69.93	0.667	0.846	71.445	22.5	49.67	72.17	143.615
Haryana	69.05	0.631	0.5626	70.243	22.21	46.05	68.26	138.503
Himachal Pradesh	57.14	0.631	0.642	58.412	17.68	55.09	72.77	131.182
Jammu and Kashmir	57.14	0.631	0.651	58.422	17.68	55.24	72.92	131.342
Jharkhand	69.93	0.667	0.949	71.546	22.5	43.29	65.79	137.336
Madhya Pradesh	69.93	0.667	1.079	71.676	22.5	41.17	63.67	135.346
Punjab	69.05	0.631	0.512	70.192	22.21	48.84	71.05	141.242
Rajasthan	69.05	0.631	0.409	70.090	22.21	26.21	48.42	118.51
Uttarakhand	57.14	0.667	0.818	58.626	17.68	59.91	77.59	136.216
Uttar Pradesh	69.05	0.723	0.860	70.632	22.21	41.45	63.66	134.292
Andhra Pradesh	70.72	0.704	0.939	72.363	22.75	42.09	64.84	137.203
Karnataka	57.14	0.667	0.911	58.719	17.68	77.14	94.82	153.539
Kerala	34.67	0.596	0.270	35.536	11.15	75.77	86.92	122.456
Tamil Nadu	46.68	0.667	0.977	48.324	14.44	41.64	56.08	104.404
Telangana	70.72	0.704	0.860	72.284	22.75	39.49	62.24	134.524
Goa	34.67	0.596	0.221	35.487	11.15	52.42	63.57	99.057
Gujarat	34.67	0.658	0.679	36.007	11.15	44.04	55.19	91.197
Maharashtra	34.67	0.596	0.828	36.094	11.15	57.23	68.38	104.474
Andaman and Nicobar and LD	57.14	0.596	0.953	58.689	17.68	101.12	118.8	177.489
Assam	57.14	0.596	1.023	58.759	17.68	39.98	57.66	116.419
Arunachal Pradesh	57.14	0.596	1.116	58.852	17.68	101.12	118.8	177.652
Mizoram	57.14	0.596	1.116	58.852	17.68	40.26	57.94	116.792
Nagaland	57.14	0.596	1.116	58.852	17.68	81.04	98.72	157.572
Odisha	40.86	0.663	0.837	42.360	16.85	46.50	63.35	105.71
West Bengal	40.86	0.663	0.935	42.457	16.85	59.88	76.73	119.187
Tripura	40.86	0.596	1.116	42.572	16.85	54.80	71.65	114.222
Others	34.67	0.667	0.930	36.267	11.15	42.00	53.15	89.417
Total	1554.23	18.075	22.7876	1595.093	504.2	1502.99	2007.19	3602.283

near Darbhanga, growing over 100,000 mango trees. This was one of the earliest examples of grafting of mangoes, including the totapuri, rataul and kesar. However, commercial mango orcharding systems in India are about more than 250 years old. The orchards are generally replanted after 50–60 years or shifted to new areas and more frequently replanted in recent decades. In any case the soils under mango orchards aged 25 years and above have attained QEV stage after accumulation of dry matter and loss of SOC over time.

As mentioned it was difficult to obtain representative state averages of soil C stocks under mango orchards. Published information is mainly restricted to agriculture ecosystems and very few to horticultural ecosystems. Since state-wise SOC stocks information was available from forest ecosystems and as mango orchards represented more closely the forest ecosystems, we used the available data for computing C stocks by mango orchards. The soil C stocks in different states varied from 26.21 tonne ha^{-1} in Rajasthan to 101.12 tonne ha^{-1} in the Bay Islands (Table 4). Other than Bay Islands, the highest C stock in major mango belts was recorded in Karnataka (77.14 tonne ha^{-1}).

The proportion of soil carbon in total C sequestered in mango orchards was higher than the tree carbon. It has been shown that the proportion of soil C in many instances exceeds the tree biomass carbon[17]. In this study the proportion of soil carbon to total sequestered C varied from 22.16% in Rajasthan, to 61.87% in Kerala with a mean of 46.97%. Other than these, the highest soil C stock in major mango belts was recorded in Maharashtra (54.77%), followed by Goa (52.42%), West Bengal and Karnataka (50.24%). Gupta[27] reported that in mango orchards in Mangalore, the soil C stock was 41 tonne ha^{-1} in the surface 50 cm depth. Chabra *et al.*[28] also reported that the soil C sequestered in Indian forest soils ranged from 37.5 tonne ha^{-1} in tropical dry deciduous forests to 92.1 tonne ha^{-1} in littoral swamp forests. Our values are for 100 cm depth soil profiles and are fairly similar to those reported in the literature for different regions.

Table 5 gives the C pool compartment of mango orchards. The mean C sequestered in mango orchards varied from 91.197 tonne ha^{-1} in Gujarat to 177.65 tonne ha^{-1} in Arunachal Pradesh. However, in the main mango belts it varied from 134.5 tonne ha^{-1} in Uttar Pradesh, Andhra Pradesh and Telangana to 153.5 tonne ha^{-1} in Karnataka.

Table 6. Carbon sequestered in mango orchards of India (tonnes)

State	Area (000 ha)	Total carbon sequestered in 1 ha orchard (tonne ha^{-1})	Total carbon sequestered in the region (mt)
Bihar	150.64	133.385	20.09312
Chhattisgarh	73.99	143.615	10.62607
Haryana	9.42	138.503	1.304698
Himachal Pradesh	41.52	131.182	5.446677
Jammu and Kashmir	12.67	131.342	1.664103
Jharkhand	52.24	137.336	7.174433
Madhya Pradesh	40.08	135.346	5.424668
Punjab	6.85	141.242	0.967508
Rajasthan	5	118.51	0.59255
Uttarakhand	35.93	136.216	4.894241
Uttar Pradesh	264.93	134.292	35.57798
Andhra Pradesh	332.97	137.203	45.68448
Karnataka	192.61	153.539	29.57315
Kerala	69.11	122.456	8.462934
Tamil Nadu	160.94	104.404	16.80278
Telangana	180.62	134.524	24.29772
Goa	4.770	99.057	0.472502
Gujarat	153.18	91.197	13.96956
Maharashtra	157.07	104.474	16.40973
Andaman and Nicobar & LD	0.05	177.489	0.008874
Assam	5.58	116.419	0.649618
Arunachal Pradesh	0.05	177.652	0.008883
Mizoram	0.89	116.792	0.103945
Nagaland	0.64	157.572	0.100846
Odisha	199.3	105.71	21.068
West Bengal	97.93	119.187	11.67198
Tripura	11.64	114.222	1.329544
Others	6.98	89.417	0.624131
Total	2262.77	3602.283	285.005

This is very low compared to wild polyembryonic mango trees grown from seeds. This is attributed to the fact that wild mango trees may reach 35–40 m or more height and live for several hundred years as against 8–10 m height and life of 40–50 years in cultivated grafted mangoes. Wild mangoes are fast-growing, erect trees with slender to broad and rounded upright canopy. On the other hand, grafted mangoes are dwarf statured, with relatively slow growth and branched at the surface. The wild trees are long-lived with some still producing fruit at 300 years of age. Whereas the orchard trees generally decline after 30 years. The wood density of wild mangoes is relatively higher (specific gravity 0.68)[29], than cultivated mangoes (specific gravity 0.52–0.55). The tree is anchored by a long unbranched taproot and can descend to greater depth plus a mass of feeder roots as against a narrow root volume of grafted mangoes. The feeder roots of wild mangoes send down anchor roots which penetrate the soil to a depth of 1.2 m and spread laterally as far as 7.5 m as against less than 1 m depth and a spread of 2–3 m in grafted mangoes. All these parameters show that the biomass productivity of grafted mangoes is far lower than cultivated grafted mangoes in the orchards.

The state-wise C sequestration by orchard mangoes was computed by multiplying the per hectare C sequestration by orchard mangoes with the area under mango cultivation in the respective states (Table 6). Andhra Pradesh and Telangana put together having maximum area under mango (332.97 + 180.62 thousand ha) had sequestered 69.98 million tonnes (mt) of C. This was followed by Uttar Pradesh (35.58 mt), Karnataka (29.57315 mt), Odisha (21.07 mt) and Bihar (20.09 mt). The country as a whole had sequestered 285.005 mt of C in its mango orchards.

In order to formulate viable strategies for climate change mitigation, it is critical to understand, on the one hand, the land-use/land-use change dynamics in a given region. On the other hand, it is essential to examine the changes in C fluxes derived from land-use change patterns. One of the first crucial steps to achieve these goals is to obtain basic information on C content associated with various stocks of natural and man-made land-use/land-use change classes at the regional level. Completing the present study involved a comprehensive effort above all in the integration of different methodologies for field work and data processing. The study generated unique information, both in terms of stocks and also allometric equations for grafted mangoes. It is thus a valuable first step for advancing our knowledge of the C cycle in cultivated mango ecosystems. Future efforts should consider other fruit crops orchards, coffee and tea estates and plantations of India and with larger sample sizes, to be able to determine C sequestered in perennial horticultural crops in the country as a whole.

The mangoes in India have mostly occupied degraded lands, although more and more orchards are coming under prime agricultural lands owing to the thrust given for horticulture in the country. Odisha, Madhya Pradesh, Chhattisgarh, Jharkhand and Bihar have large tracts of tribal land, and waste and degraded lands. These regions are suitable for a variety of mangoes like amrapali, Dasheri, Neelachal, Kesari, etc. Maharashtra itself has about 17% of the Konkan region as waste land. This is the region occupied by the famous Alphonso mangoes. In Konkan Goa and Karnataka also Alphonso mango occupied similar soils. Such regions are to be brought under productive mango orchards. Similar efforts may be made to bring the Chambal ravines under mangoes. Consequently, where forests have disappeared, such lands may be brought under mangoes, which reasonably imitate forests and sequester carbon in similar quantities and can augment climate-change risks. The administrators in these regions must use this information for claiming carbon credits to benefit the farmers and the local population.

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