BIOTROPIA Vol. 30 No. 3, 2023: 374 - 383 DOI: 10.11598/btb.2023.30.3.2005

ANNUAL CARBON CAPTURE POTENTIAL IN BANANA GARDENS OF INDIA

A.N. GANESHAMURTHY

Division of Natural Resources Management, Indian Institute of Horticultural research, Bengaluru 560089. India

Received 9 April 2023 / Revised 13 August 2023 / Accepted 13 August 2023

ABSTRACT

The global interest in increasing the world's carbon stocks is skewed towards perennial woody ecosystems. But a continuous shortage of land stands in the way of achieving the goal. We must therefore aim to explore viable alternatives. The banana as a potential carbon sequester attracted little attention from researchers. Therefore, this study aimed at estimating the potential of bananas in different states of India as potential carbon sequesters. Data was collected from twelve major banana producers between January 2021 and December 2022. One hundred banana gardens were sampled in each of the 12 banana-producing states, covering the major bananas grown (AAA, AAB, and ABB). The above-ground (AGB) and below-ground (BGB) biomass were calculated using the allometric equation with pseudostem volume as the allometric parameter. The dry weight obtained from the allometric equations was then converted to carbon using a dry weight to carbon conversion factor. Sequestered carbon varied with the AAA, AAB, and ABB of bananas. Banana plant carbon stock was also found to be very small, ranging from 2.573 to 6.407 t/ha, compared with very high soil carbon ranging from 39.55 to 77.14t. In all the banana-cultivating states, the proportion of carbon contained in the plant to that in the soil was only 8.286 percent, and that of soil carbon accounted for 91.714%. At the national level, the banana crop sequestered 48.627 million metric tonnes of carbon, with soil carbon accounting for 44.798 metric tonnes and plant carbon accounting for only 3.828 metric tonnes per year. Despite these small amounts of plant carbon, the banana cropping system enriches the soil by enabling much more carbon to be sequestered into the soil in amounts comparable to other perennial plantations.

Keywords: AAA, AAB, ABB, Banana growing states, banana stock estimation, carbon stock, cultivars, plant carbon, SOC.

INTRODUCTION

The giant herb Bananas of the Musaceae family and *Musa* genus are widespread throughout the tropical and subtropical zones (Charrier *et al.* 1997). It has occupied the 6th position in the world's fruit production and is a vital part of human diets in many regions. About 130 countries grow bananas, which they produce (Reay 2019). More than a thousand cultivars' and bred varieties with an array of sizes, colours, and shapes are under cultivation. These include yellow-skinned, red-skinned, and sweet table varieties, as well as starchy plantains used for cooking. They are nutritionally rich in minerals such as potassium and zinc, as well as essential vitamins A and C (Ravi 2013). The genome assemblies that constitute the entire spectrum of edible bananas and plantains, such as AAA, AAB, or ABB, are designated as "groups, while the total set of a basic cultivar and its derived clones form a "subgroup" (Langhe *et al.* 2000). AAA and AAB Group generally have stem diametres of 20–25 cm, grow to a height of 3–4 metres with broad leaves that range from 2 to 3 metres in length, and produce a high yield of medium-sized fruit. The ABB group is smaller, with a stem diameter of 15-20 cm and a leaf size of 2–3 meters in length, and produces high yields of larger fruit.

Banana is cultivated commercially under tropical and subtropical conditions all over the world, both on a commercial scale and by smallholders for home consumption or sale at local markets. The Asia-Pacific region produces

[*]Corresponding author, email:

55.4% of global production, and India ranks first in production, accounting for nearly 26.3%. Central and South America also contribute significantly to the total world banana basket (FAO 2018, Statista 2022). About a thousand varieties of bananas are produced, but preferences for varieties are generally local. The bananas of the AAA group, mainly the Cavendish type, are the most cultivated and produce about 50 billion metric tonnes, accounting for roughly 47 percent of global production (FAO 2022). (Nkoulou *et al*., 2023). The volume of production and trade of all other local bananas (AAB and ABB groups) is greater than that of Cavendish bananas.

India, with its wide variability of soil and climate, produces a large number of fruits. Among them, eight fruit crops occupy more than 80% of the fruit crop area, and bananas are the third most widely grown after mango and citrus, occupying 20% of the total fruit area and producing one-third (3184,000 metric tonnes) of the total fruits produced in India.

When huge quantities of bananas are produced to meet the livelihoods of millions of people around the world, it has naturally spurred climate-smart actions that include multidimensional and interconnected challenges to minimise GHG emissions and ensure sustainability (UNGA, 2015). This is because banana cultivation in the past concentrated on the need to increase food production and ignored the need to protect the environment, water, and biodiversity, thereby contributing to considerable environmental degradation and the loss of crop diversity. Realising this agricultural diversity and diversity-based farming have been advocated as the major backbones of sustainable agricultural intensification and a sustainable food system (Tutwiler *et al*. 2017). In terms of GHG emissions, a kilogramme of bananas results in the emission of 0.5–1.3 kilogrammes of greenhouse gas, or 100 to 200 grammes per banana (Reay 2019). Parts of the banana's life cycle can be targeted directly to mitigate climate change (WRAP 2012).

The banana crop leaves a large amount of residue. It is estimated that about four metric tonnes of pseudostem remain at the harvest location for each tonne of fruit harvested (Souza *et al*. 2010). Some estimates show that from the total of harvested bananas, 1.5 t of leaves and 2.5 t of pseudostem are generated per tonne of banana produced (Oliveiraa 2013). These residues contribute greatly to carbon sequestration, alcohol production, and natural fibre production. Making use of this biomass for the extraction of fibre and nutrients (particularly potassium), the production of alcohol for fuel, etc., could be a very attractive alternative by not only contributing to the preservation of the environment through carbon sequestration and removing this waste from the land but also by adding value to the fruit production matrix and transforming the residue into a commodity (Soraishram *et al*. 2021; Souza et al., 2010). Banana can be considered a perennial crop; thus, there is relatively permanent standing biomass throughout the year with considerable carbon content in its structure and hence a potential carbon sequester. Given the perennial and morphological nature of a crop like banana, it is worthwhile exploring its contribution to the carbon cycle. We therefore estimated the total annual banana residues produced and tried to work out their carbon sequestration potential in India.

MATERIALS AND METHOD

Selection of gardens and sampling

Banana is grown in many states of India, and the area (880 thousand ha) varies extensively, with large localised pockets (Fig. 1) located in different agroecological regions (Table 1). One hundred banana gardens were sampled in each of the top 12 banana-producing states, covering the major bananas grown (AAA, AAB, and ABB) in these respective states, as presented in Table 1.

A banana plant produces fruits only once during its lifespan. But new stalks are continuously produced from each plant. The fruit is harvested around 9 to 11 months after planting; then, the new stalks produce fruits every 3 to 4 months (Elbehri *et al*. 2015). The selected gardens are commercial-scale monocropping production systems with field histories of banana production spanning more than 20 years. We estimated the annual biomass production per plant and did not include the suckers that go to the next crop cycle.

An extensive survey was conducted in these regions to record allometric data. In each state, 100 gardens at the harvest stage were randomly sampled to obtain a fairly representative sample of the gardens in these states. Given the variability in plant population and yield per hectare across different cultivated varieties, the determination of state-specific plant population per hectare for banana cultivation was guided by productivity considerations. Specifically, states exhibiting productivity levels exceeding 30 tonnes (primarily falling within the AAA group) were assigned a plant population of 4440 plants per hectare, while states with productivity below 30 tonnes per hectare (mainly within the AAB and ABB groups) were allocated a plant population of 2267 plants per hectare. Flowers, flower bracts, and flower stock constitute about This value was used to compute the carbon contribution from this component. Weed biomass in banana gardens is very low, so this parameter was not included in this study.

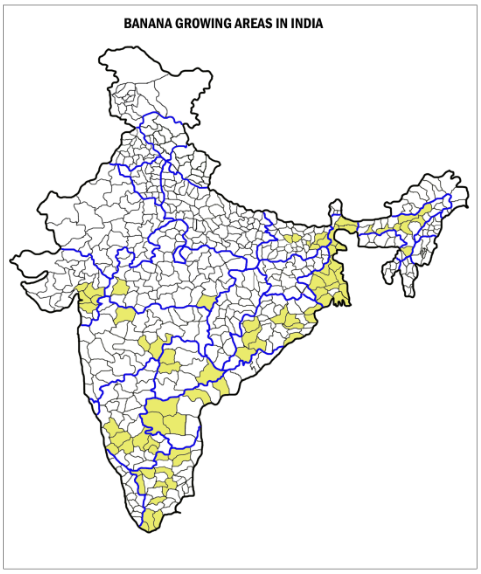

Fig 1 District boundaries of major Banana growing areas in India (Map not to scale)

Table 1 Banana growing States and districts with varieties, area, production and productivity.

State	Districts	Varieties	Area, 000 ha (% share)	Production 000 Mt (% share)	Productivity t/ha
Andhra Pradesh &Telangana	East Godavari, West Godavari, Kurnool, Cuddapah	Dwarf Cavendish, Robusta, Rasthali, Amritpant, Thellachakrakeli, Karpoora Poovan, Chakrakeli, Monthan and Yenagu Bontha	91.25 (10.33%)	5093.10 (16.53%)	56.24
Assam	Goalpara, Nagaon, Sonitpur, foothills of Garo hills	Jahaji (Dwarf Cavendish), Chini Champa, Malbhog, Borjahaji (Robusta), Honda, Manjahaji, Chinia (Manohar), Kanchkol, Bhimkol, Jatikol, Digjowa, Kulpait, Bharat Moni	53.08 (6.00%)	913.27 (2.96%)	17.20
Bihar	Vaishali, Katihar, Kishanganj, Bhagalpur (Naugachia) and Purnia.	Dwarf Cavendish, Alpon, Chinia , Chini Champa, Malbhig, Muthia, Kothia , Gauria	31.07 (3.51%)	1396.39 (4.53%)	44.94
Gujarat	Surat, Vadodara, Anand, Kheda, Junagadh, Narmada, Bharuch	Dwarf Cavendish, Lacatan, Harichal (Lokhandi), Gandevi Selection, Basrai, Robusta, G-9, Harichal, Shrimati	68.15 (7.71%)	4472.32 (14.51%)	65.63
Jharkhand	Ranchi, Sahebganj	Basrai, Singapuri	9.17 (1.03%)	32.06 (0.10%)	3.49
Karnataka	Bangalore, Chitradurga, Shioroga, Hassan, Chikka Mangloor	Dwarf Cavendish, Robusta, Rasthali, Poovan, Monthan, Elakkibale	110.55 (12.50%)	2328.90 (7.56%)	21.07

Table 1 (Continued)

Kerala	Thiruvananthapuram, Kollam, Pathanamthitta, Alappuzha, Kottayam, Idukki, Ernakulam, Thrissur, Palakkad, Malappuram, Kozhikode, Wynadu, Kannur, Kasargod	Nendran (Plantain), Palayankodan (Poovan), Rasthali, Monthan, Red Banana, Robusta	109.26 (12.36%)	1119.16 (3.63%)	10.24
Madhya Pradesh	Khandwa, Badwani, Khargaon, Dhar	Basrai, Grand Naine, Robusta,	26.38 (2.98%)	1834.03 (5.95%)	69.54
Maharashtra	Jalgaon, Ahmednagar, Buldhana, Pune, Wardha, Dhule, Nanded, Parbani, Nandurbar, Satara, Sangli, Osmanabad, Buldhana, Akola, Yeothmal, Amravati, Thane, Kulara, Alibag	Dwarf Cavendish, Basrai, Robusta, Lal Velchi, Safed Velchi, Rajeli Nendran, Grand Naine, Shreemanti, Red Banana	80.88 (9.15%)	4209.27 (13.66%)	52.05
Orissa	Ganjam, Puri, Khurda, Gajpati, Cuttack, Dhenkanal, Angul, Sundargarh, Sambalpur, Bargarh, Deogarh, Koraput, Keonjhar, Raygada, Mayurbhanj	Dwarf Cavendish, Robusta, Champa, Patkapura (Rasthali)	24.20 (2.74%)	449.82 (1.46%)	18.59
Tamil Nadu	Thoothukudi, Tiruchirapalli, Coimbatore, Tirunelveli, Karur, Erode, Kanniyakumari	Virupakshi, Robusta, Rad Banana, Poovan, Rasthali, Nendran, Monthan, Karpuravalli, Sakkai, Peyan, Matti	82.63 (9.35%)	3205.04 (10.40%)	38.79
West Bengal	Hooghly, Nadia, North 24 Parganas	Champa, Mortman , Dwarf Cavendish, Giant Governor, Kanthali, Singapuri	49.30 (5.57%)	1200.00 (3.89%)	24.34
Other states			150.14 (28.77%)	4464.12 (14.49)	29.73
All India			883.77ha	30807.5	34.86

Source: DAC & FW, 2018.

Ganeshamurthy (2023) developed a universal banana allometric equation for nondestructive estimation of the above-ground biomass (AGB) of a standing banana crop at the harvest stage. This involved measuring the volume of the pseudostem as the allometric parameter. Briefly, the allometric equation was developed through destructive sampling of AAA, AAB, and ABB groups at the harvest stage. Allometric parameters such as plant height, diameter of the stem at the base, diameter of the stem at breast height, and volume of the pseudostem were measured. Different statistical models, like linear, exponential, polynomial, and power models, were used to estimate the plant biomass of individual and combined groups of bananas. Based on the best fit, the power model with pseudostem volume as an allometric parameter was used for the estimation of plant biomass (Ganeshamurthy, 2023). The below-ground biomass was estimated using the shoot-to-root ratio of 0.235 suggested by Ganeshamurthy (2023). We used the allometric equation given below for the estimation of banana biomass for computing the CS.

AAA group: Y=0.008X0.513
AAB group: Y=4E-06X1.233
ABB group: Y=4E-06X1.22

Measurement of pseudostem volume

The diameter of the stem at the base above the ground and below the bunch was measured with the help of a Vernier caliper. The pseudostem volume was calculated by multiplying the stem diameter at the base by the diameter below the bunch, as follows:

$$V = 1/3 \times \pi h(R^2 + Rr + r^2)$$

Where:
R = radius at the stem's base

r = radius beneath the bunch such that R > r
h = height from the base of the plant to bunch level expressed in cubic centimeters

Carbon estimation

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

Soil carbon stocks

Getting representative data on the soil carbon stock of a region is a difficult task. Arriving at a state-wise average SC stock was practically impossible because the data is not available for a political boundary-based average SC as no such effort has been made in India (Ganeshamurthy *et al.* 2019). Further, the available resources were generated from agricultural lands, mainly cultivating annual crops, and hence do not represent a perennial crop system. The Forest Survey of India has made efforts to generate state-wise soil carbon stocks of forests, and the latest data was published in 2017. By and large, banana gardens imitate a disturbed forest ecosystem. Therefore, we used this data to calculate the state average values for SC. The method adopted by FSI is similar to those normally adopted to estimate soil carbon stocks. Briefly, the method followed by FSI for collecting the data on SC is given here.

RESULTS AND DISCUSSION

The volume of the banana pseudostem, the basic growth parameter used for calculating the AGB, varied from state to state (Table 2). This depended mainly on the type of bananas cultivated in these states. The data obtained from Assam, Kerala, Orissa, Tamil Nadu, and West Bengal was above. In Andhra Pradesh, Karnataka, and Telangana states, the recorded pseudostem volume ranged between 50000 and 60000 cm^3. The lowest volumes below 50000 cm^3 were recorded in other states. This variation in the data is mainly accounted for by the type of bananas grown in these states and the climate and management practices adopted by farmers in these regions. Among the states, bananas in Gujarat recorded the lowest mean pseudostem volume (46576 cm^3), and Assam recorded the highest mean value (62731 cm^3). Stevens et al. (2020) reported similar pseudostem volumes for banana plants producing about 2–3 kg of above-ground biomass for two contrasting cultivars.

Table 2 Mean allometric parameters (Vpseudostem, cm^3) and tree carbon sequestered in banana gardens in India

States/UT	Range	Mean	SD	Median	Q2	Q3
Andhra Pradesh & Telangana	45872-63324	54490	5227	54236	52117	56428
Assam	53450-73419	62731	5714	63726	59442	66885
Bihar	32089-63127	45763	1204	45341	41287	47220
Gujarat	31680-62885	46576	1218	46550	42824	49729
Jharkhand	31821-62231	44563	1320	48035	45176	51022
Karnataka	45889-63267	54602	5281	54493	50668	57260
Kerala	53244-73427	62636	5216	63288	59117	67335
Madhya Pradesh	31380-62859	47706	3165	47360	46819	49715
Maharashtra	31416-62865	47631	3052	47256	46358	49021
Orissa	53425-73376	62822	5798	63284	59776	68221
Tamil Nadu	53351-73396	62831	5845	63349	61264	65108
West Bengal	53452-73417	62960	5802	62826	59871	64332
Other states	45927-63316	54721	5108	54774	52285	57064
All India	31380-73427	54618	4150	52268	41220	68376
	Mean of 100 plants					

Danarto and Hapsari (2015) reported that cultivars of banana with "B" genomes (AAB and ABB cultivars) are more vigorous and contribute higher biomass and C-stock than the cultivars having only "A" genomes (AAA group). Our results supported this argument. States like Maharashtra, Andhra Pradesh, Telangana, and Madhya Pradesh, which grow mainly Cavendish bananas (AAA), recorded lower AGB (2.5 kg/plant) and BGB (0.550 kg/plant). Whereas other states cultivating varieties belonging to the AAB and ABB groups recorded higher AGB (>2.5 kg/plant) and BGB (>0.550 kg/plant). Nyombi *et al.* (2009) reported a plant dry weight of 1.44 kg/plant for the pseudostem alone for a similar variety of banana in East Africa. Ortiz-Ulloa *et al.* (2020) also reported similar values for bananas grown in two different regions. Stevens *et al.* (2020) reported similar AGB for two contrasting cultivars. Our values are comparable to those reported in the literature.

The mean carbon content in the pseudostem was 0.465%, and that of the root and corm was 0.471%. The carbon capture in the AGB and BGB was then computed using these values (Table 3). The AGB carbon captured by bananas varied from the lowest at 0.920 kg/plant in Jharkhand to the highest at 1.395 kg/plant, and the BGB carbon varied from the lowest at 0.218 kg/plant in Jharkhand to the highest at 0.332 kg/plant in West Bengal. It is reported that on a per-plant basis, the ABB group sequestered higher carbon, followed by the AAB group, and the least in the AAA group (Nyombi *et al.* 2009; Ortiz-Ulloa *et al.* 2020). Andhra Pradesh, Gujarat, Jharkhand, Madhya Pradesh, Maharashtra, and Telangana mainly cultivate Cavendish-type (AAA group) bananas. Hence, the carbon capture per plant in these states is lower. In Assam, Karnataka, Kerala, Orissa, Tamil Nadu, and West Bengal, we mainly cultivate both AAB and ABB group bananas, capturing the least carbon per plant.

Total carbon capture by bananas per ha depends on the plant population per ha and carbon capture per plant. In carbon capture, two distinct groups can be seen in different states. The differences among states are mainly accounted for by the types of bananas cultivated in these states. The data on total carbon captured per ha (Table 4) obtained from Andhra Pradesh, Bihar, Gujarat, Madhya Pradesh, and Maharashtra (where mainly AAA group bananas are cultivated) were above 5 t/ha. In Assam, Jharkhand, Karnataka, Kerala, Orissa, Tamil Nadu, and West Bengal states (where mainly the AAB and ABB group bananas are cultivated), the recorded carbon capture was below 5 t/ha. This shows that, on a per-ha basis, the AAA group bananas capture more carbon than the AAB and ABB group bananas. It means that all those states cultivating AAA group bananas sequester about 1.3 to 1.5 fold more carbon per hectare than other states growing AAB and ABB group bananas. Ortiz-Ulloa *et al.* (2020) reported that CS by banana in four provinces in Ecuador ranged from 4.18 t/ha to 5.44 t/ha. They accounted for this variability in CS in the plant population. In our study, too, the differences in CS in different states growing different groups of bananas were

Table 3 Biomass and carbon sequestered in banana gardens in India(Mean of 100 plants)

States/UT	*AGB,* Kg/plant	Major Banana group	BGB Kg/plant	AGB C, Kg/ plant	BGB C, Kg/ *plant*	Total C, Kg / plant	Total C, t/ha
Andhra Pradesh & Telangana	2.507	AAA	0.589	1.166	0.277	1.443	6.407
Assam	2.994	AAB&ABB	0.704	1.392	0.331	1.724	3.908
Bihar	2.025	AAA	0.476	0.942	0.224	1.166	5.177
Gujarat	2.061	AAA	0.484	0.958	0.228	1.186	5.265
Jharkhand	1.972	AAB&ABB	0.463	0.920	0.218	1.135	2.573
Karnataka	2.512	AAB&ABB	0.590	1.168	0.278	1.446	3.278
Kerala	2.989	AAB&ABB	0.702	1.390	0.331	1.721	3.901
Madhya Pradesh	2.110	AAA	0.496	0.981	0.235	1.215	5.394
Maharashtra	2.108	AAA	0.495	0.980	0.233	1.214	5.390
Orissa	2.998	AAB&ABB	0.705	1.394	0.332	1.726	3.912
Tamil Nadu	2.998	AAA	0.705	1.394	0.332	1.726	3.912
West Bengal	3.000	AAB&ABB	0.705	1.395	0.332	1.727	3.915
Other states	2.517	AAB&ABB	0.591	1.170	0.279	1.449	3.284
All India	2.522		0.593	1.173	0.279	1.452	4.332

mainly due to differences in the plant population per ha. AAA bananas are planted closely, accommodating 4444 plants per ha. Whereas the AAB and ABB group bananas are planted with wider spacing, accommodating 2267 plants per ha. Edible banana cultivars have lower biomass and C-stock values than wild bananas. Danarto and Hapsari (2015) reported a CS of 9.7 kg/plant in Klutuk Wulung, an AAA variety, and 4.74 kg/plant in another variety, Klutuk Ijo, that belongs to the ABB group. These data support the finding that AAA produces lower CS than ABB. However, their values are higher because these varieties are from backyard gardens where solitary plants have grown very robustly. Ours are commercial gardens with high-density planting. Hence, our values reported here are lower than those reported by Danarto and Hapsari (2015). Our values fairly match those reported by Ortiz-Ulloa *et al.* (2020) and Stevens et al. (2020) from commercial gardens.

Soil carbon

Organic C in the soil fluctuates based on the canopy cover over the surface. Quasi-equilibrium (QEV) of SOC is attained over a long period of time, varying from 500 to 1000 years in a forest system. In the agriculture system, this is attained in about 30–50 years after land use change from forest to agriculture and in 30 years for the horticultural system (Arrouays *et al.* 1995; Batjes 2001; Dickson and Crocker 1953; Jenny 1950; Johnson 1995; Naitam and Bhattachaarya 2004). During the process of stabilisation, the SOC shows tooth-like cycles of accumulation and loss during the beginning years and slowly attains an equilibrium level after the accumulation of dry matter and loss of SOC over time. It has been shown that under these tropical land uses, horticultural systems attain QEV in about 25 years (Ganeshamurthy 2012). All the selected banana gardens in this study had a history of banana cultivation spanning more than 20 years. Therefore, the soils under these gardens might have attained the QEV stage after the 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 banana gardens. Published information is mainly restricted to agricultural ecosystems and very few to horticultural ecosystems. Since state-wise SOC stock information was available from forest ecosystems and since sites under continuous banana gardens represented forest ecosystems more closely, we used the available data for computing C stocks by banana gardens. The status of SOCs in Karnataka and Kerala is relatively higher because of the favourable climate. Whereas the plant carbon content in Andhra Pradesh and Telangana is higher because of the bright sunshine hours prevailing in these states relative to other banana-growing states.

Table 4 Soil and plant carbon pools in banana gardens in India

States/UT	Soil C t/ha	Plant carbon, t/ha	Area (000 ha)	Total soil carbon stock 1000 tons	Total plant carbon stock 1000 tons	Total CS in Banana gardens,mt
Andhra Pradesh & Telangana	42.09	6.407	91.25	3840.713	584.639	4.425
Assam	39.98	3.908	53.08	2122.138	207.437	2.330
Bihar	39.55	5.177	31.07	1228.819	160.849	1.390
Gujarat	44.04	5.265	68.15	3001.326	358.810	3.360
Jharkhand	43.29	2.573	9.17	396.969	23.594	0.421
Karnataka	77.14	3.278	110.55	8527.827	362.383	8.890
Kerala	75.77	3.901	109.26	8278.630	426.223	8.705
Madhya Pradesh	41.17	5.394	26.38	1086.065	142.294	1.228
Maharashtra	57.23	5.390	80.88	4628.762	435.943	5.065
Orissa	46.50	3.912	24.2	1125.300	94.670	1.220
Tamil Nadu	41.64	3.912	82.63	3440.713	323.249	3.764
West Bengal	59.88	3.915	49.3	2952.084	193.010	3.145
Other states	50.69	3.284	150.14	7610.597	493.060	8.104
All India	50.69	4.332	883.77	44798.301	3828.492	48.627
% contribution to the total CS				91.714	8.286	100.000

Total C sequestered in orchards

The soil and plant carbon pools in banana gardens are presented in Table 5. The soil carbon pool is very large compared to the plant carbon pool. It contributed more than 86% of the total CS in banana gardens. The mean contribution of SOC varied from 86.8% in Andhra Pradesh to 95.9% in Jharkhand. At the national level, the SOC contributed 91.71% to the total CS.

The plant carbon pool, on the other hand, is very small compared to the soil carbon pool. The plant carbon pool contributed less than 15% in all the states. The lowest contribution from plant C to the total CS was recorded in Karnataka (4.08%) and Kerala (4.90%), and the highest contribution was recorded in Andhra Pradesh (13.21%) and Madhya Pradesh (11.58%). At the national level, Plant C contributed 8.29% to the total CS.

The carbon content of banana plants accounted for only 8.286 percent of the total CS in banana gardens. The contribution of each state to the total carbon sequestered by banana plants alone depended upon the area and varieties of bananas under cultivation in these states and the quantity of SOC. Andhra Pradesh with the highest area under banana (91.25 thousand ha) cultivating mainly the AAA group bananas sequestered 584639 metric tonnes of carbon, whereas Jharkhand with the lowest area under banana (9.17 thousand ha) cultivating mainly the AAB and ABB group bananas sequestered the lowest plant carbon (23594 metric tonnes). On an all-India basis, the total plant carbon sequestered accounted for 3828492 metric tonnes. The study clearly indicated that under banana gardens, SC is the major C pool, accounting for 91.7%, and plant carbon is only a small portion, accounting for 8.29% of the total CS.

Kamusingize et al. (2017) reported that the SOC contribution to total CS under bananas exceeded 90% in Ugandan banana gardens. In their study, the total SOC stock beneath all cultivars was considerably high, ranging from 81 to 92 mg ha^{1}. The plant carbon in these studies was found to be very small, ranging between 0.37 and 1.64 mg ha^{1}. Danarto and Hapsari (2015) reported that, on average, various Indonesian bananas captured around 2.26 kg (or 0.98 tonne) per hectare. Thus, banana crops enrich soil by investing carbon into the soil through huge root biomass and over time during photosynthesis as carbon moves from the vegetative canopy into the soil (Turner, 2003; Hairiah et al., 2010). Published information on SOC in banana gardens in India is not available for a fair comparison. Therefore, it can only be made from the data published on other fruit crop systems such as mango, sapota, guava, and forest systems. Gupta (2011) reported that the soil C stock was 41 tonne ha^{1} at the surface and 50 cm deep. Chabra *et al.* (2003) 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 ha1 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. The banana cropping system enables much more carbon to be stored in the soil, despite the fact that banana cultivars contain small average amounts of plant carbon stocks. Kamusingize *et al.* (2017) and Danarto and Hapsari (2015), in their study, reported that the proportion of carbon contained in the plant to that in the soil across all cultivars was in the range of 0.4–2%. Large soil carbon stocks in banana cropping systems could perhaps be attributed to the sustainable agricultural land management practices employed by farmers, such as mulching, the use of trenches to minimise erosion, and minimal and no tillage (Lal 2011, Paswel *et al.* 2012, Joris *et al.* 2013). Investing in the proper management of banana plantations is invaluable for contributing to SOC as a major carbon pool in banana systems.

The crop demography in India is changing fast towards perennial horticulture. This results in land-use change in the region. Therefore, we must examine the related changes in C fluxes derived from such land-use change patterns in different regions to formulate viable strategies for climate change mitigation. The present study generated unique information on banana gardens in India. This involved a comprehensive effort in the integration of different methodologies for field work and data processing. But on a national scale, there is a need to generate information on all such perennial horticulture systems, such as other fruit crop orchards, coffee and tea estates, and plantations in India, with larger sample sizes to be able to determine the percentage of carbon sequestered in perennial horticultural crops in the country as a whole.

The land-use change patterns are occurring mainly on prime agricultural lands due to increased demand for bananas. Bihar, Jharkhand, Odisha, Madhya Pradesh, and Chhattisgarh have large tracts of tribal land. These regions are suitable for banana cultivation. Such regions are to be encouraged for productive banana cultivation. Similar efforts may be made in other states as well, which reasonably imitate forests and sequester carbon in similar quantities and can augment climate change risks. The information generated in this study may be used by the administrators in these regions to claim carbon credits to benefit the farmers and the local population.

CONCLUSIONS

This study showed a significant difference in total plant carbon stock across different cultivars and states in India. There was a significant difference between groups of bananas in their ability to sequester carbon. Soil carbon stocks were very high,ranging from 39.55 to 6.407 t/ha. But plant carbon stocks were found to be very small,ranging from 2.573 to 6.407 t/ha. In all banana-cultivating states, the proportion of carbon contained in the plant to that in the soil was only 8.286 percent. Soil carbon accounted for the majority of the total CS, accounting for 91.714%. Despite these small amounts of plant carbon, the banana cropping system enriches the soil by enabling much more carbon to be sequestered into the soil. Apart from augmenting fruit production, expanding the area under banana farming systems helps to rehabilitate the landscape, decrease carbon emissions in the form of biomass and carbon stocks, and meet the economic needs of the region.

REFERENCES

Arrouays D, Isabelle V, Luckicin J. 1995. Spatial analysis and modelingof top soil carbon storage in temperate forest humic loamy soil ofFrance. Soil Science. 159, 191-198.

Batjes N.H. 2001.Options for increasing carbon sequestration in West African soils: An exploratory study with special focus on Senegal. Land Degradation and Development. 12, 131-142.

Charrier A, Jacquot M, Hamon S, Nicolas D. 1997. *L'amélioration des plantes tropicales*. Montpellier (FRA) ; Paris : CIRAD ; ORSTOM, 624 p. (Repères). ISBN 2-87614-292-9. ISSN 1251-7224.

Chhabra A, Palria S, Dadhwal A. K. 2003. Soil organic carbon pools in Indian forests. For. Ecol. Manage. 2003. 173: 187-199.

DAC & FW 2018. Horticultural Statistics at a Glance 2018, Horticulture Statistics Division, Department of Agriculture, Cooperation & Farmers Welfare (DAC&FW), Ministry of Agriculture & Farmers Welfare, Government of India.

Danarto S.A, Hapsari L. 2017. Biomass and carbon stock estimation inventory of indonesian bananas (musa spp.) and its potential role for land rehabilitation. Biotropia. 22: 102-108.

Dickson B.A, Crocker R.L. 1953. A chronosequence of soils andvegetation near Mt. Shasta, California, I and II. Soil Science. 4: 142-154.

Elbehri A, Calberto G, Staver C, Hospido A.2016. *Ecuador's Banana Sector Under Climate Change*. Food and Agriculture Organization of the United Nations. http://www.fao.org/3/a-i5697e.pdf

FAO. 2018. *Reducing Carbon and Water Footprints in Banana Plantations*. Food and Agriculture Organization of the United Nations. http://www.fao.org/world-banana-forum/projects/reducing-carbon-and-water-footprints-in-banana-plantations/en/

FAO. 2022. Banana: 2022. https://www.fao.org/markets-and-trade/commodities/bananas/en/#:~:text=More%20than%201%20000%20varieties,volume%20of%2050%20million%20tonnes

FSI, 2017. Carbon stocks in India's forests. In India State of Forest Report 2017 Chapter 8.0, Forest Survey of India.

Ganeshamurthy 2012. Annual Report, ICAR-Indian Institute of Horticultural Research, Bengaluru

Ganeshamurthy A.N, Ravindra V, Rupa T.R, Bhat R.M. 2019.Carbon Sequestration Potential of Mango Orchards in India Current Sci. 117(12): 2006-2013.

Gupta M. K.2011. Soil organic carbon pools under different land use in Haridwar district of Uttarakhand. Indian For., 137: 1-8. 28.

Hairiah K, Dewi S, Agus F, Velarde S, Ekadinata A, Rahayu S, Van N.M. 2010. Measuring carbon stocks across land use systems: A Manual, Bogor, Indonesia. World Agroforestry Centre (ICRAF), SEA Regional Office. 155p.

Jenny H. 1950. Causes of high nitrogen and organic matter content ofcertain tropical forest soils. Soil Science. 69: 63-69.

Johnson M.G. 1995. The role of soil management in sequestering soilcarbon. In 'Soil management and greenhouse effects'. (Eds R Lal,JM Kimble, RF

Follet, BA Stewart) pp. 351–363. (Lewis Publishers,Boca Raton, FL).

Joris A, Leo D.N, Anne G. 2013. Valuing the carbon sequestration potential for European agriculture. Land Use Policy 31: 584-594.

Kamusingize D, Mwanjalolo J.M, KomutungaE, Tumwebaze S, NowakundaK, Namanya P Kamu J.K. 2017. Carbon sequestration potential of East African Highland Banana cultivars (Musa spp. AAA-EAHB) cv. Kibuzi, Nakitembe, Enyeru and Nakinyika in Uganda. Journal of Soil Science and Environmental Management. 8: 44-51.

Lal R. 2011. Sequestering carbon in soils of agro-ecosystems. Food Policy 36:S33-S39. De Langhe E. 2000. Diversity in the genus Musa, its significance and its potential. ActaHort. 540: 81-86.

Naitam, R and Bhattachaarya, T. Quasi-equilibrium of organic carbon in shrink–swell soilsof the subhumid tropics in India under forest, horticulture, andagricultural systems. Australian Journal of Soil Research. 2004. 42, 181-188

Nkoulou L.F.M, a b f, Ninla L.A.T, Cros,D, Martin G, Ndiang Z, Houegban J, Ngalle H.B, Bell J.M, Achigan-Dako E.G. 2023. Analysis of genetic diversity and agronomic variation in banana sub-populations for genomic selection under drought stress in southern Benin. Gene. 859, 147210

Nyombi K, Van Asten P.J.A, Leffelaar P.A, Corbeels M, Kaizzi C.K, Giller K.E. 2009. Allometric growth relationships of East Africa highland bananas (Musa AAA-EAHB) cv. Kisansa and Mbwazirume. Ann. Appl. Biol. 155: 403-418.

Oliveira C.D, Donato S.L.R, Mizobutsi G.P, Silva J.D, Mizobutsi E.H. 2013. Características pós-colheita de bananas 'Prata-Anã'e' BRS Platina'armazenadas sob refrigeração. Revista Brasileira Fruticultura. 35(3): 891-897.

Ortiz-UlloaJ.A, Abril-Gonzalez M.F, Pelaez-Samaniego M.R, Silvana T. 2020. Biomass yield and carbon a batement potential of banana crops (*Musa* spp.) in Ecuador. Environmental Science and Pollution Research. https://doi.org/10.1007/sl1356-020-09755-4.

Paswel M, Ephraim N, Wei X, Jose D, Edward K. 2012. Which policy would work better for improved soil fertility management in subSaharan Africa, fertilizer subsidies or carbon credits? Agric. Syst. 110: 162-172.

Ravi I, Uma S, Vaganana M, Mustafa M. 2013. Phenotyping bananas for drought resistance. Frontiers in Physiology 4(9): 1-14.

Reay D.2019. Climate-Smart Food. eBook.https://doi.org/10.1007/978-3-030-18206-9.

Saranya S, Aneesa Rani M.S, Raveendran M, Kalaiyarasi R and Auxcilia J. 2021. Molecular characterization of diploid and triploid banana germplasms through DNA finger printing using ISSR markers.The Pharma Innovation Journal 2021; 10(10): 1876-1882.

Soraisham L.D, Gogoi N, Mishra L, Basu G. 2021. Extraction and Evaluation of Properties of Indian Banana Fibre (Musa Domestica Var. Balbisiana, BB Group) and Its Processing with Ramie. J.Natural Fibewrs. https://www.researchgate.net/deref/https%3A%2F%2Fwww.tandfonline.com%2Floi%2Fwjnf20

Souza E.L, Sellin N, Marangoni C, Souza O. 2010. The Influence of Different Strategies for the Saccharification of the Banana Plant Pseudostem and the Detoxification of Concentrated Brothon Bioethanol Production. Appl Biochem Biotechnol. 183: 943-965.

Statista 2022. Volume of banana produced across India from financial year 2015 to 2021, with an estimate for 2022. https://www.statista.com/statistics/1038905/india-production-of-banana/

Stevens B, Diels J, Brown A, Bayo S, Ndakidemi P.A, Swennen R. 2020. Banana Biomass Estimation and Yield Forecasting from Non-Destructive Measurements for Two Contrasting Cultivars and Water Regimes. Agronomy 10: 1435.

Turner D.W. 2003. Factors affecting the physiology of the banana root system. In: Turner DW, Rosales FE (Eds) Banana Root System: Towards a better understanding for its productive management. Proceedings of an international symposium held in San Jose, Costa Rica. pp. 107-113.

Tutwiler M.A, Bailey A, Attwood S, Remans R, Ramirez M. 2017. Agricultural biodiversity and food system sustainability Transformation. In book: Mainstreaming Agrobiodiversity in Sustainable Food Systems.

UNFCC 2020.The clean development mechanism. Mechanisms under the Kyoto Protocol, In https://unfccc.int/process-and-meetings/the-kyoto-protoco1/mechanisms-under-the-kyoto-protocoI/th e-cIean- development-mechanism.

WRAP. 2013. Household food and drink waste in the United Kingdom 2012. Waste and Resource Action Programme. http://www.wrap.org.uk/sites/files/wrap/ hhfdw-2012-main.pdf.pdf .