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RESEARCH ARTICLE

Carbon sequestration potential of *Casuarina equisetifolia* plantations at harvest age in tropical region of India

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Abstract

Studying the carbon stock of tree plantations is essential for mitigating climate change, as trees act as carbon dioxide sinks by fixing carbon during photosynthesis and storing excess carbon as biomass. With a significant emphasis on the role of carbon in global warming, Afforestation/Reforestation (A/R) activities have the potential to provide a "sink" for carbon from our atmosphere and act as a reservoir. In current study, the sequestered carbon dioxide from atmosphere by Casuarina plantations was calculated and converted into carbon by a particular plantation using the globally accepted formula developed by the IPCC. Simultaneously, the soil organic carbon of the particular Casuarina plantations was also estimated. Finally, the carbon stock of *Casuarina equisetifolia* plantations were estimated under different management practices. The various management practices like pruning, irrigation and fertilizer application also improves the carbon sink potential of the tree plantations. The mean carbon concentration ranged from 41% (leaf litter) to 46% (wood) in the different components of *Casuarina equisetifolia.* The plantations recorded a carbon accumulation of 9.12 Mt C ha^{-1} year^{-1} in biomass components alone at the harvest age of 3 years in the tropical region of Tamil Nadu, India. Proper management practices in tropical regions worldwide have the potential to further enhance carbon stocks in plantations. This data will be ready reckoner for future Clean Development Mechanism (CDM) projects for controlling global warming.

Keywords

carbon sequestration; carbon table; *Casuarina equisetifolia*; CDM projects; tropical region

Introduction

Carbon dioxide (CO_2) and carbon monoxide (CO) are the primary greenhouse gases produced by industrial activities and urbanization. These gases contribute significantly to global warming and ozone layer depletion. Ongoing global warming suggests that CO_2 will need to be reduced from its current level to at most 360 ppm (parts per million), but likely less than that. As of March 2023, atmospheric carbon dioxide levels have risen to 420 ppm, far exceeding the target of 360 ppm to mitigate global warming (1). In 1988, a global effort was initiated to address the issue of greenhouse gases (GHGs) in the earth's atmosphere and to provide a comprehensive scientific assessment of the current state of the climate change threat to Earth's atmosphere and this led to the establishment of the Intergovernmental Panel on Climate

Change (IPCC). The IPCC serves as the foremost authority for the assessment of climate change. It was established under the joint auspices of the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO). This scientific organization's role is to examine and evaluate the latest global scientific, technical and socioeconomic information related to climate change, contributing to a better understanding of this complex issue.

On the other hand, the United Nations established the 'United Nations Framework Convention on Climate Change (UNFCCC)' at the 1992 Rio Earth Summit. This forum was created to address the challenges posed by climate change. Based on the UNFCCC, the Protocol imposed a greater responsibility on big, industrialized countries, directed by the principle of "common but differentiated responsibilities" and Kyoto Protocol emerged as a part of the solution to address the rising carbon dioxide (CO_2) and other greenhouse gases (GHGs) levels in the atmosphere. Those commitments commit to reducing greenhouse gas emissions by an average of 5.2% compared to 1990 levels. Those emission reductions had to take place in the "first commitment period" continues from 2008 to 2012. An important decision was made regarding the forest sector of the Clean Development Mechanism (CDM). This decision involved the inclusion of "Afforestation and Reforestation (A/R)" as a feasible method for mitigating atmospheric carbon.

Forests are characterized as having high productivity, complex structures and being the most expansive biological systems among all terrestrial ecosystems. The investigation and assessment of long-term carbon pool dynamics in tropical regions are crucial subjects of inquiry and scholarly discourse. The forests in tropical and dry regions are shrinking rapidly and Carbon reserves of these wooded area ecosystems are under threat of diverse biotic and abiotic forces (2). In Global Land area, Tropical forests covering only 7% and have great Carbon sequestration potential accounting for about 20% of the world's forest carbon sink (3). Hence, the carbon stock of tree species in Tropical region of the world is very important to reduce the global warming. Carbon storage potential depends on several factors such as tree species, soil type, local climate, topography and management practices and although information and research in this area are rapidly increasing, in practice is not well documented. The faster a tree grows; the faster carbon is sequestered from the environment.

There are many potentially fast-growing species suitable forsuchA/R (Afforestation/Reforestattion) activities like Eucalyptus, Poplar, Pinus, bamboos, etc. *C. equisetifolia* has been yet another species not only of relevance to carbon sequestration but also presents a practical alternative for meeting the raw material needs of the paper industry (4). Although quick harvesting of *C. equisetifolia* (3-4 years) reduces the safety span of carbon locking, paper produced from *C. equisetifolia* recycled for longer periods will compensate the disadvantage of short rotation plantation as regards the carbon release.

In India, plantations are concentrated in the coastal areas which account for about 80% of the total geographical area of the country. It is also estimated that about 5000 km^2 are planted with *C. equisetifolia* in the coastal region of India (5). At present, *C. equisetifolia* is one of the important species being planted on a large scale through contract farming by various paper mills in India. As one of the most productive and rapidly growing plants on Earth, *C. equisetifolia* holds significant potential as a valuable carbon storage sink. At present, information on carbon sequestration of these plantations is not available particularly in Tropical region of the world and therefore this study was undertaken in the East coast region of Tamil Nadu, India to estimate carbon sequestration of Casuarina and also to develop carbon stock in biomass components of *C. equisetifolia* which will be a ready reckoner for developing future CDM projects in global level. Based on the above background, the present study was proposed with the following objectives

1. To estimate the carbon stock in *Casuarina equisetifola* plantations at harvest age (3 years) under different management regimes
2. To develop carbon table for *Casuarina equisetifola* plantations in Tropical region of Tamil Nadu, India

Materials and Methods

This study was conducted through the sampling of *C. equisetifolia* trees in coastal areas of different agro-climatic zones of Tamil Nadu (Fig. 1). 35677 ha of Casuarina plantations reported in the state during the study period (6), out of this 99% of the plantations are located in the 3 coastal agro-climatic zones where this study was conducted. The sampling done in each Agro-climatic zone was proportionate to the actual extent of plantation of Casuarina in the respective zone. The harvesting should be carried out in before the onset of monsoon i.e., the months of April and May. On an average, the sampling intensity adopted was 1% in all the 3 agro-climatic zones studied (Table 1).

Dry matter production of sample trees

Carbon studies were conducted in 69 plantations of *Casuarina equisetifolia* in 3 coastal agro-climatic zones of Tamil Nadu. Out of 69 plantations, 80% of the plantations were with spacing of 1 m x 1 m and casualty of trees recorded varied from 3 to 20%.

Table 1. Details on extent of plantations of Casuarina area and the sampled plantations and the Sampling Intensity in four Coastal agro-climatic zones of Tamil Nadu

Zone No	Name of the agro-climatic zone	Extent of plantations of Casuarinas (ha)	Total area of sampled plantation (ha)	Sampling Intensity (%)
I.	Northeastern zone	42676	470.5	1.10
IV.	Cauvery delta zone	2268	23.7	1.04
V.	Southern zone	497	5.4	1.09
VI.	High rainfall zone	16	Nil	Nil

Source: Tamil Nadu state Directorate of Economics and Statistics, 2022

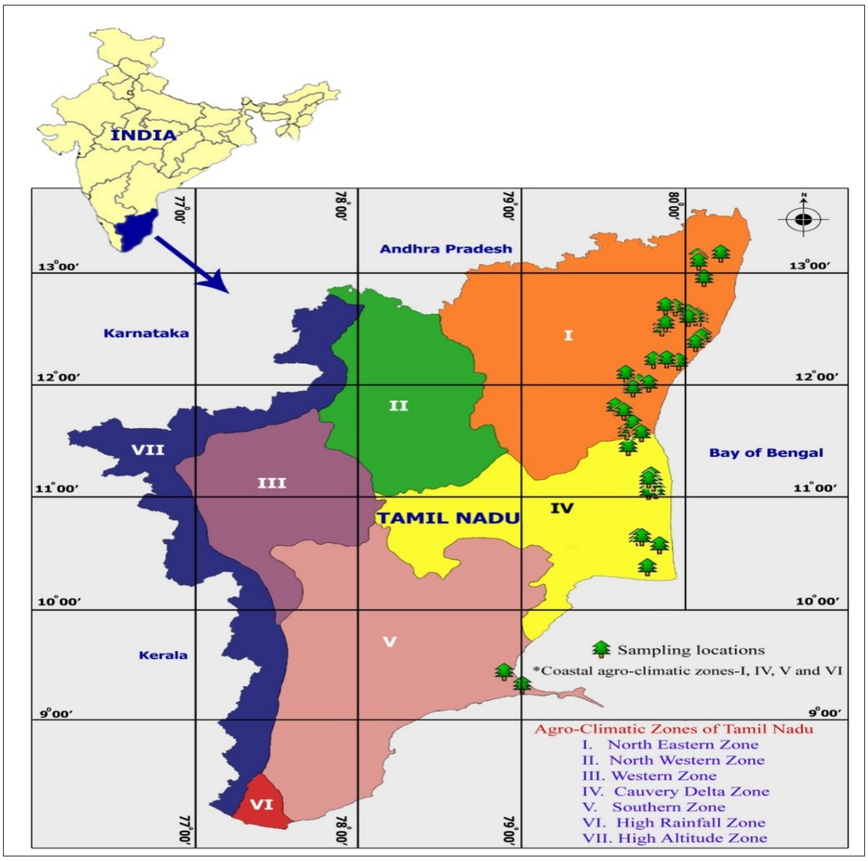

Fig. 1. Study locations – East coastal region of Tamil Nadu, India.

Sampling method

The sampling method used in this study is the "Stratified Average Tree Technique," as introduced by Art and Marks, 1971. In this method, 10 x 10 m sample plots were established and the Girth at Breast Height (GBH) of every tree within those plots were measured and recorded. The entire range of girth measurements was then divided into 3 classes using a frequency distribution approach. Within each girth class, one average tree was chosen for sampling. Consequently, 3 average trees were felled from all the plantations, finally total of 200 trees being collected for the purpose of estimating both above-ground and below-ground biomass.

Sample trees were cut close to the ground with a hacksaw and their total height was recorded. All branches and twigs were then removed from the main trunk. Needles (phyllocladodes) were also separated from the twigs. The main bole was limited to 5 cm thicker end girth. Green weight of main stem, branches, twigs and needles were recorded separately in the field. Representative samples from each component were taken and fresh weight of samples of all the components was measured in the field itself. The samples were transported to laboratory for dry weight estimation and carbon analysis (Fig. 2).

The main bole was cut into 1 m billets to make more accurate estimation of Dry Matter Production (DMP) in stem by minimizing the axial variations in stem from stump to canopy height. A 5 cm thick disc was taken from the cut ends of each billet. In the field, the bark and wood of the discs were separated and their respective fresh weights were recorded. Subsequently, all the discs and bark were placed in paper bags and transported to the laboratory for dry weight estimation and carbon analysis. Once in the laboratory, the collected samples were subjected to oven drying at 60 °C until a consistent weight was achieved. The dry weights of the different components were then calculated based on the initial fresh weight and the final dry weight of representative samples. Dry weight of wood and bark of each billet was estimated using mean wood: bark ratio of 2 successive discs. The dry weight of each billet was totalled separately to obtain the dry weight of bark and wood of the main bole. Sample trees were cut close to the ground with a hacksaw and their total height was recorded. All branches and twigs were then removed from the main trunk. The biomass of each sample plot was calculated after multiplying the weight of each sample tree by the number of trees in each surrounding class and adding the above values to obtain the total biomass. From the above plot level biomass, biomass per hectare basis was computed. The roots of the specimen trees were excavated using the skeletal method, i.e. dry excavation. This method involves digging along the path of the roots in the ground. The total fresh weight of the core stump, main root, lateral roots and small accessory roots was measured in the field. Representative samples from these 3 root categories were selected and their fresh weights were measured in the field. The dry weight of these samples was estimated in the laboratory. The biomass of fine roots (<2 mm diameter) and small roots (2-5 mm diameter) was determined by sorting these roots from soil cores. Coarse roots were sampled by taking several pieces at random to represent all sizes for dry weight estimation. Soil monoliths of 10 cm thick and 50 cm^2 sizes were taken to estimate the biomass of fine roots.

a. Diameter measurement at breast height.

b. Tree harvesting.

c. Tree length measurement.

d. Stem converted into small billets.

e. Disc from each billet.

f. Stem biomass estimation.

Fig. 2. Stratified average tree technique.

Litter accumulation studies

Out of 69 plantations studied, litter was collected only from 29 plantations in 3 agro-climatic zones using 1m x 1 m sample plots. In the remaining 40 plantations, litters were parted or fully removed by owners or by common public for fuel purpose. In plantations wherein litter layer is exposed to such disturbances, litter study was not conducted. Fresh weight of the collected litter samples was recorded in the plantation itself. The dry weight of the litter was determined by subjecting it to a constant temperature of 60 °C in a hot air oven until a constant weight was achieved.

Carbon estimation

The carbon content of all samples was determined using the ash content method. Oven-dried plant components such as needles, twigs, stems, bark, roots and litter were baked in a Muffle furnace (GENTECH make) at a temperature of 550 °C. The remaining ash, consisting of inorganic elements in the form of oxides, was weighed and the carbon content was calculated. This calculation was done following the equations provided by (7-10).

Carbon% =

100-(Ash Weight + molecular weight of O_2 (53.3) in$C_H H_{12} O_6$)

The carbon stock in the agb, bgb and the litter was estimated using the following formula:

Carbon (Mt)=Biomass (Mt) x Carbon %

Estimation of Soil Organic Carbon (SOC)

Composite soil samples were collected from 0 to 30 cm depth in all 69 plantations. The collected soil samples were air-dried in the shade and ground into fine soil particles using a mallet. The soil prepared in this way was first sieved through a 0.5 mm sieve and stored in soil bags. A small amount of each sample was sieved through a 0.2 mm sieve for analysis of organic carbon and other nutrients. Undisturbed soil masses were collected from each layer and stored for bulk density measurements. Bulk density was measured using the bulk method and the measured bulk density was corrected by the proportion of coarse particles. Corrected bulk density (mg m^{-3}) was used to estimate soil organic carbon density (mg ha^{-1}) and soil organic carbon stock. Soil organic carbon content in 0.2 mm sieved soil samples was estimated following Walkley and Black's wet oxidation method (11).

Soil stoniness and land use were recorded. Soil samples were analysed for bulk density, organic carbon and texture. The soil organic carbon stock Qi (mg m^{-2}) in the soil layer or sampling surface i of depth Ei (m) is defined by the carbon content Ci (g C g^{-1}) and the bulk density Di (Mg m^{-2}). Then find the volume fraction Gi of the coarse element using the formula (12).

$$Qi = CiDiEi\ (I\text{-}G)$$

where,

Qi – soil organic carbon stock (mg m^{-2})

Ei – depth (m)

Ci – carbon content (g C g^{-1})

Di – bulk Density (mg m^{-3})

Gi – coarse fragments

Carbon pool estimation

Five carbon pools in any plantation or forest ecosystems are above ground, below ground, dead material, litter and SOC. Out of these 5 carbon pools, dead materials are negligible because *C. equisetifolia* plantations are harvested at very short rotation of 3-5 years and most of the dead materials are collected for fuel at frequent intervals. For calculation of other 4 carbon pools, only plantations of harvest age were considered and total carbon worked out and presented in Mt C ha^{-1}. Total carbon of different carbon pools was worked out for plantations in different agroclimatic zones, different soil types and different management practices (irrigated and rain-fed lands, with fertilizer application and without fertilizer application) in coastal region of Tamil Nadu. The data obtained from these studies were used to perform regression and other statistical analysis using SPSS® 28.0 version and Microsoft® Excel™ 2021 (13).

Results

Carbon concentration in different biomass components of *Casuarina equisetifolia*

Ash content analysis was used to measure the carbon concentration of various biomass components *viz*., needle, twig, branch, wood, bark, root and litter of *Casuarina equisetifolia* (Table 2). The mean carbon concentration ranged from 41 to 46% in different components of *C. equisetifolia.* It was observed that woody tissues like wood (46%), branches (45%), twigs (45%) and root (44%) contained a higher carbon concentration than soft tissues like bark (43%), needle (42%) and litter (41%). Compared with other biomass components, stem wood registered more carbon concentration because of carbon storage in the form of cellulose in main stem.

Carbon stock of C. equisetifolia plantations at harvest age in 3 agro-climatic zones

In the present study, out of 5 major carbon pools of any forest plantation ecosystem *viz*., i) aboveground biomass ii) below ground biomass, iii) detritus or dead organic materials, iv) litter and v) soil organic carbon, 4 carbon pools were assessed in plantations of *Casuarina equisetifolia* except dead materials which were absent or negligible in quantity. The results are presented hereunder.

Large amounts of carbon were detected in aboveground biomass in all 3 agroclimatic zones studied (Table 3). Northeastern zone recorded the maximum above ground carbon stock (25.94 Mt C ha^{-1}) followed by Cauvery Delta zone (18.99 Mt C ha^{-1}) and Southern zone recorded the least aboveground carbon stock (14.79 Mt C ha^{-1}) (Table 3). Second major carbon pool in *C. equisetifolia* plantations was SOC. Soil organic carbon was almost equal in Northeastern and Cauvery Delta zones (17.60 and 17.16 Mt C ha^{-1}) and the least SOC has recorded in Southern zone (12.28 Mt C ha^{-1}). Third major carbon pool in *C. equisetifolia* plantations were below ground root biomass. In below ground root biomass

Table 2. Carbon concentration (%) in different biomass components of *Casuarina equisetifolia*

Serial no.	Components	Carbon concentration (%)		
		Minimum	Maximum	Mean*
1.	Needle	41	43	42 ± 0.35
2.	Twig	44	46	45 ± 0.18
3.	Branch	45	46	45 ± 0.14
4.	Wood	44	46	46 ± 0.05
5.	Bark	43	44	43 ± 0.15
6.	Root	43	45	44 ± 0.27
7.	Litter	41	42	41 ± 0.15

*Mean carbon value with ± standard error

Table 3. Carbon sequestration potential (metric tonnes of carbon per ha) of *C. equisetifolia* plantations at harvest age in 3 agro-climatic zones in Coastal region of Tamil Nadu

Carbon pool	Northeastern zone*	Cauvery delta zone*	Southern zone*
Above ground	25.94 ± 2.14	18.99 ± 1.64	14.79 ± 2.63
Below ground	5.15 ± 0.35	4.22 ± 0.71	2.97 ± 0.57
Litter	3.06 ± 0.77	4.26 ± 0.79	1.45 ± 0.28
Soil organic carbon	17.60 ± 1.35	17.16 ± 2.37	12.28 ± 0.12
Total carbon	**51.75**	**44.63**	**31.49**

*Mean carbon value with ± standard error carbon stock was highest in Northeastern zone (5.15 Mt C ha^{-1}) followed by Cauvery Delta zone (4.22 Mt C ha^{-1}) and Southern zone (2.97 Mt C ha^{-1}). With regard to carbon stock in litter, the maximum litter carbon stock was recorded in Cauvery Delta zone (4.26 Mt C ha^{-1}) and next by Northeastern zone (3.06 Mt C ha^{-1}). Again, the least litter carbon stock was recorded in Southern zone (1.45 Mt C ha^{-1}). The total carbon stock of all carbon sinks was greater in the Northeast region having carbon stock of 51.75 Mt C ha^{-1} than in Cauvery Delta zone (44.63 Mt C ha^{-1}) and Southern zone (31.49 Mt C ha^{-1})

Carbon stock of C. equisetifolia plantations at harvest age in different soil types

The carbon stocks in 4 carbon pools were worked out for plantations in 3 soil types and the results are presented in Table 4. Alfisol recorded the maximum aboveground carbon stock (27.99 Mt C ha^{-1}) followed by Inceptisol (22.30 Mt C ha^{-1}). Vertisol recorded the least aboveground carbon stock (17.63 Mt C ha^{-1}). With reference to the second largest carbon pool of soil organic carbon, the greater carbon stock was recorded in Vertisol (25.07 Mt C ha^{-1}) than in Alfisol (18.80 Mt C ha^{-1}) and Inceptisol (13.17 Mt C ha^{-1}). In belowground carbon stock in root biomass, Alfisol (5.26 Mt C ha^{-1}) registered higher carbon stock than Inceptisol (4.74 Mt C ha^{-1}) and Vertisol (3.80 Mt C ha^{-1}). The litter carbon stock was also larger in quantity (4.31 Mt C ha^{-1}) when compared to Inceptisol (2.75 Mt C ha^{-1}) and Vertisol (2.70 Mt C ha^{-1}). In turn, the total carbon stock in all the 4 carbon pools were greater in Alfisol having carbon stock of (56.36 Mt C ha^{-1}) as compared to Vertisol (49.2 MtC ha^{-1}) and Inceptisol (42.96 Mt C ha^{-1}).

Carbon Stock of C. equisetifolia plantations at harvest age under different carbon pools in irrigated and rain-fed lands

The carbon stocks were worked out in 4 carbon pools under 2 types of lands based on irrigation. In comparison of irrigated with the rain-fed lands carbon stock was higher in all the carbon pools in irrigated lands except in belowground biomass. In all 4 carbon pools aboveground biomass recorded more carbon stock compared with the other carbon pools in both irrigated (Flood irrigation) and rainfed lands (23.86 and 19.66 Mt C ha^{-1} respectively). Then next second major carbon pool or soil organic carbon was higher in irrigated lands (18.09 Mt C ha^{-1}) compare with rainfed lands (12.98 Mt C ha^{-1}). But belowground root biomass was having more carbon stock in rain-fed lands (4.83 Mt C ha^{-1}) than irrigated lands (4.67 Mt C ha^{-1}). Litter recorded the least carbon stock in *C. equisetifolia* plantations. Irrigated lands had more litter carbon stock (3.45 Mt C ha^{-1}) than rainfed lands (3.20 Mt C ha^{-1}).

Table 4. Carbon sequestration potential (metric tonnes of carbon per ha) of *C. equisetifolia* plantations at harvest age in various soil types in Coastal region of Tamil Nadu

Carbon pool	Inceptisol	Alfisol	Vertisol
Above ground	22.30 ± 2.20	27.99 ± 3.43	17.63 ± 0.66
Below ground	4.74 ± 0.50	5.26 ± 0.59	3.80 ± 0.46
Litter	2.75 ± 0.65	4.31 ± 1.07	2.70 ± 0.14
Soil organic carbon	13.17 ± 0.52	18.80 ± 0.97	25.07 ± 3.17
Total carbon	**42.96**	**56.36**	**49.2**

*Mean carbon value with ± standard error

Carbon Stock of C. equisetifolia plantations at harvest age in farmlands with fertilizer and without fertilizer application

Carbon stock was higher in all the carbon pools in lands with fertilizer application (Diammonium phosphate at the rate of 50 g per plant in 2 split doses per year for first 2 years). In all the 4 carbon pools aboveground biomass was having more carbon stock compared with the other carbon pools in lands both with fertilizer and without fertilizer application (25.46 and 22.15 Mt C ha^{-1} respectively). As per the results, fertilizer application field can improve the yield of 13% per ha than the without fertilizer application field. Then the next major carbon pool is SOC. Soil organic carbon was higher in lands without fertilizer application (17.34 Mt C ha^{-1}) than with fertilizer application (16.08 Mt C ha^{-1}). Then the third major carbon pool is belowground biomass, where with fertilizer application, lands were having more carbon stock (4.82 Mt C ha^{-1}) than without fertilizer application (4.65 Mt C ha^{-1}). Litter recorded the least carbon stock in *C. equisetifolia* plantations and lands with fertilizer application had more litter carbon stock (4.82 Mt C ha^{-1}) than without fertilizer application (4.65 Mt C ha^{-1}).

Carbon tables for C. equisetifolia in Tamil Nadu

Finally, from this study we developed Carbon table for *C. equisetifolia* in Tamil Nadu. Table 5 shows carbon table for aboveground biomass of *C. equisetifolia*. All biomass components (needle, twig, branch, stem and bark) are separately converted into carbon with the help of separate prediction equation. The following equations were used for different biomass components:

Needle : $y = 0.008 X2 + 0.234 X + 0.132$

Twig : $y = 0.127 X^{0.682}$

Branch : $y = -0.004 X^2 + 0.229 X + 0.586$

Stem : $y = 1.458 X^{0.787}$

Bark : $y = 0.246 X^{0.787}$

Table 5. Carbon table for above ground biomass of *Casuarina equisetifolia* (kg C tree^{-1}) in Tamil Nadu. The values outside the thick lines are beyond the range of observed data

Diameter at breast height (cm)	Carbon for above ground biomass (kg C tree^{-1}) Height (m)										
	5	6	7	8	9	10	11	12	13	14	15
3	**0.793**	0.884	0.976	**1.067**	1.157	1.247	1.338	1.429	1.519	1.610	1.701
4	**1.148**	**1.308**	**1.470**	**1.630**	**1.790**	**1.949**	**2.109**	**2.268**	2.427	2.584	2.742
5	1.600	1.850	**2.098**	**2.346**	**2.593**	**2.840**	**3.087**	**3.331**	**3.577**	3.820	4.064
6	2.149	2.506	2.861	**3.202**	**3.569**	**3.920**	**4.271**	**4.620**	**4.968**	**5.314**	5.659
7	2.791	3.273	3.752	4.230	**4.706**	**5.176**	**5.649**	**6.115**	**6.583**	**7.054**	7.505
8	3.527	4.154	4.773	5.390	6.004	**6.609**	**7.217**	**7.818**	**8.416**	**9.005**	**9.596**
9	4.358	5.143	5.919	6.691	7.457	**8.212**	**8.967**	**9.712**	**10.455**	11.183	11.910
10	5.271	6.229	7.186	8.126	9.043	9.974	10.889	11.788	12.683	**13.558**	**14.432**

Finally, for all the biomass components carbon value was added and presented as total carbon for aboveground biomass in *C. equisetifolia* for Tamil Nadu. Carbon value ranged from 0.793 to 14.432 kg C tree^{-1} when diameter ranges from 3 to 10 cm and height ranges from 5 to 15 m.

Table 6 shows carbon values for belowground biomass and root carbon value was calculated with the help of following prediction equation: (y = 0.616 $X^{0.832}$). Belowground biomass carbon for *C. equisetifolia* ranged from 0.139 to 2.561 kg C tree^{-1} when diameter ranges from 3 to 10 cm and height ranges from 5 to 15 m.

Discussion

Plantations act as carbon sinks when they absorb CO_2 from the atmosphere, subsequently releasing oxygen and retaining carbon. The hardwoods contain about 48% of carbon in their stem. It is necessary to produce 2.2 tonnes of wood to sequester one tonne of carbon. The carbon sequestration potential of forests diminishes as trees approach maturity. In mature forests growth rate is largely balanced by wood decay. In other words, trees' ability to sequester carbon from the atmosphere is not determined solely by climate and global environmental factors which are location/region specific but also a function of its age.

The CO_2 absorption rate is directly proportional to the growth rate. Many workers estimate carbon storage by assuming that the carbon content of the dry biomass remains constant at 50% by weight (14-21). Generally, carbon allocation is calculated by multiplying the dry biomass by a default value of 0.5, but this does not represent the actual carbon stock. There are instrumental methods which are expensive. Therefore, in the current study, we used the ash content method to estimate the actual carbon content of different plant parts of *C. equisetifolia*.

Tropical forests and plantations available in tropical regions play an important role in carbon sequestration. In tropical dry deciduous forest ecosystems in Jhumpa and Kairu, southern Haryana, India, the net primary productivity of trees ranged from 8.1 to 9.6 Mg ha^{-1} y^{-1}r, with trees sequestering significant amounts of carbon in both the soil and plant biomass (2). A study assessed the above and belowground carbon stock in a tropical forest in Brazil and reported the total estimated carbon stock was 267.52 mg ha^{-1}, of which 35% was in aboveground biomass, 63% in soil and 2% in roots (22).

Carbon concentration in different biomass components of *C. equisetifolia*

The mean carbon concentration ranged from 41 to 46% in different components of *C. equisetifolia.* Compared with other biomass components, stem wood registered more carbon concentration (46%) because of carbon storage in the form of cellulose in main stem. This was consistent with previous findings in Eucalyptus plantations in Southern Brazil (23), Southern China (24), Uruguay (25).

The same method was followed in *Hevea brasiliensis* (9) and in *Populus deltoides* (26). It was reported carbon concentration in *Tectona grandis* as 41% in stem to 44% in root (8); carbon concentration in *Cassia siamia* ranged from 39% in leaves to 47% in stem; carbon concentration in *Dalbergia sissoo* ranged from 41% in leaves to 45% in the stem. It is reported that carbon concentration was different in different plant tissues of *Hevea brasiliensis* which was estimated through ash content method (16). It ranged from 49% in leaves to 57% in stem. A similar result was reported by another study, in *Poplar* species in China (27). Moreover, it was also found that more carbon concentration in wood than in other biomass components of *Pinus roxburghii, Pterospermum acerifolium, Syzygium cumini, Tectona grandis* and *Dendrocalamus strictus* (28). The results of the present investigation are also having same findings as previous research report (7, 29-32).

The pattern was in the following descending order; wood > branches > twigs > root > bark > needle > litter. The difference between the lower and higher concentration of carbon in all the biomass components was worked out and compared. It is observed that the greater difference in carbon concentration was in needle component (difference between minimum and maximum concentration being 3%) followed by wood and root (having the difference in minimum and maximum values being 2%).

Carbon Stock of *C. equisetifolia* plantations at harvest age in 3 agro-climatic zones

The present results were supported by many researchers. Different research workers reported carbon stock in different ecosystems and plantations which ranged from 31.07 Mt C ha^{-1} (33) to 61.06 Mt C ha^{-1} (34-36) reported intermediate value of C ha^{-1} in above range. It was obtained from a study that carbon stock in wood ranged from 16.98 to 17.20 Mt C ha^{-1} in plantations (37). A 10-year-old *Poplar* plantations in China sequestered 72 Mt C ha^{-1} at the density of 1111 stem ha^{-1} (27). Similar result was

Table 6. Carbon table for below ground biomass of *Casuarina equisetifolia* (kg C tree^{-1}) in Tamil Nadu

Diameter at breast height (cm)	Carbon for below ground biomass (kg C tree^{-1})										
	Height (m)										
	5	6	7	8	9	10	11	12	13	14	15
3	**0.139**	0.161	0.184	**0.205**	0.225	0.247	0.267	0.287	0.306	0.326	0.346
4	**0.224**	**0.260**	**0.296**	**0.331**	**0.364**	**0.398**	**0.431**	**0.463**	0.495	0.527	0.558
5	0.324	0.377	**0.429**	**0.479**	**0.529**	**0.577**	**0.624**	**0.672**	**0.717**	0.763	0.808
6	0.439	0.511	0.581	**0.649**	**0.715**	**0.780**	**0.846**	**0.909**	**0.971**	**1.034**	1.095
7	0.567	0.660	0.751	0.839	**0.926**	**1.010**	**1.093**	**1.176**	**1.257**	**1.335**	1.414
8	0.709	0.825	0.936	1.048	1.155	**1.260**	**1.366**	**1.467**	**1.568**	**1.669**	**1.768**
9	0.862	1.003	1.141	1.275	1.405	**1.533**	**1.661**	**1.784**	**1.908**	**2.030**	2.150
10	1.027	1.195	1.360	1.519	1.677	1.830	1.979	2.126	2.272	**2.418**	**2.561**

Best-fit equation used for construction of table: y = 0.616 $X^{0.832}$

The values outside the thick lines are beyond the range of observed data.

reported for 8-year-old *Populus deltoides* plantations in Tarai, central Himalaya (38). At 6 years' age, average above ground tree biomass carbon for *Shorea robusta, Albizia lebbeck, Tectona grandis* and *Artocarpus integrifolia* were assessed at 5.22, 6.26, 7.97 and 7.28 Mt C ha^{-1} respectively (39). It was reported above ground carbon stocks of old tree plantations in Southern Ghana (40).

In the present study, carbon sequestration on an annual basis was worked out. On an average it amounted to 16.69 Mt C ha^{-1} $year^{-1}$. Greater amount of carbon in a forest ecosystem is majorly stored in aboveground biomass (41). Quantifying annual aboveground biomass carbon storage of 4 juvenile species were 0.87 Mt C ha^{-1} $year^{-1}$ for *Shorea robusta*, 1.04 Mt C ha^{-1} $year^{-1}$ for *Albizia lebbeck*, 1.33 Mt C ha^{-1} $year^{-1}$ for *Tectona grandis* and 1.21 Mt C ha^{-1} $year^{-1}$ for *Artocarpus integrifolia* (39). A plantation of 20 years old of hybrid poplar (*Populus* spp.) in Minnesota yield has reported from 1.8 to 3.1 Mt C $ha^{-1}year^{-1}$ (42). It was estimated that in 20 years after planting a total of about 2.5 Mt C ha^{-1} $year^{-1}$ could be sequestered in above ground tree biomass carbon in Conifers (43). *Ficus religiosa* recorded more carbon (4.91 Mt $ha^{-1}year^{-1}$) compared with other 19 tree species in Aurangabad and our estimated annual aboveground biomass carbon stocks were higher than the above studies (44). Compared to other tree species, *C. equisetifolia* sequesters more carbon in a short period of 3 to 4 years. *Moringa oleifera* has lower carbon content compared to *Terminaria arjuna, Azadirachta indica, Vachellia nilotica, Milletia pinnata, Album rebecca, Gmelina arborea, Dalbergia sissoo* and *Justicia adhatoda*. It was reported to be superior in terms of carbon dioxide sequestration. The total tree carbon density varied from 48.97 to 214.97 mg C ha^{-1} in tropical dry deciduous forests in Central India (45).

Carbon Stock of C. equisetifolia plantations at harvest age in different soil types

The carbon sequestration potential of *C. equisetifolia* plantations at harvest age under different soil types were assessed. Greater dry matter productivity combined with more SOC in Alfisol led to greater carbon sequestration in this soil. Though the dry matter production was higher in Inceptisol, SOC was observed to be very less and in turn total carbon sequestration value was lesser in Inceptisol. On the other hand, dry matter productivity was lesser in Vertisol but very highly SOC compensated the less dry matter productivity and in turn total carbon sequestered was greater in Vertisol than in Inceptisol.

As presented earlier, the black clayey Vertisol soils limit the productivity in AGB and root biomass and in turn lesser carbon storage in biomass components. However, the great potential of this Vertisol soil in stocking more carbon as SOC compensated this and in turn total carbon stock was greater than that in Inceptisol. Conversely, carbon stocks in biomass components were highest in plantations established in Inceptisols, but SOC was lower and total carbon stocks in Inceptisols were lowest. Sequestration also varied among soil types and its management reported in a stydy in various tree plantations (46).

Carbon stock of C. equisetifolia plantations at harvest age under different carbon pools in irrigated and rain-fed lands

For total carbon stock under 4 carbon pools irrigated land was registered more carbon stock (50.07 Mt C ha^{-1}) than rain-fed lands (40.67 Mt C ha^{-1}) (Fig. 3). As reported earlier, belowground biomass was maximum in rain-fed lands, which also turns higher carbon stock in root biomass. In terms of percentage, 24% more carbon was sequestrated in irrigated lands than the rain-fed lands. It was reported that total C stocks were for 343 Mg ha^{-1} for *Pinus radiate* plantations at the age of 20-24 years (47), 352 mg ha^{-1} for Eucalyptus nitens and 254 mg ha^{-1} for *Eucalyptus globulus* plantations at the age of 10-14 years in Chile. 27 years old *Eucalyptus grandis* plantations of mid-elevational areas of Sri Lanka sequestered 20% more carbon compare with grasslands (48).

Carbon sequestration potential of C. equisetifolia plantations at harvest age in farmlands with fertilizer and without fertilizer application

With a combination of all the 4 carbon pools, lands with fertilizer application had more carbon stock (50.12 Mt C ha^{-1}) than without fertilizer application (47.46 Mt C ha^{-1}) (Fig. 4). Both above ground carbon sequestration potential and soil carbon sequestration can increase under hybrid poplar in response to fertilization (49).

Permanency of sequestered carbon in plantations of C. equisetifolia

Fast-growing tree plantations play an effective role in capturing CO_2 and as a result, help mitigate the pace of climate change. Recent research indicates that once a forest matures, its capacity to absorb carbon diminishes, underscoring the environmental advantages of such plantations. When a tree is harvested, the carbon it stores remains preserved within the wood product and is not released. For instance, in the context of books, paper can persist in our libraries for extended periods. When paper is recycled, the duration for which carbon remains sequestered gradually extends.

The primary raw material used in paper manufacturing is cellulose fiber sourced from wood, which is a natural and renewable resource. The efficient utilization of pulp fibers is achieved through the recovery and recycling of used paper, ultimately leading to its conversion back into

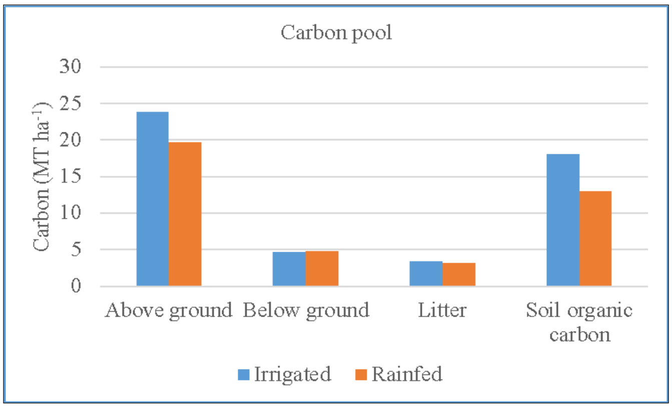

Fig. 3. Carbon sequestration potential (metric tonnes of carbon per ha) of *C. equisetifolia* plantations at harvest age in irrigated and rain fed lands in coastal region of Tamil Nadu, India.

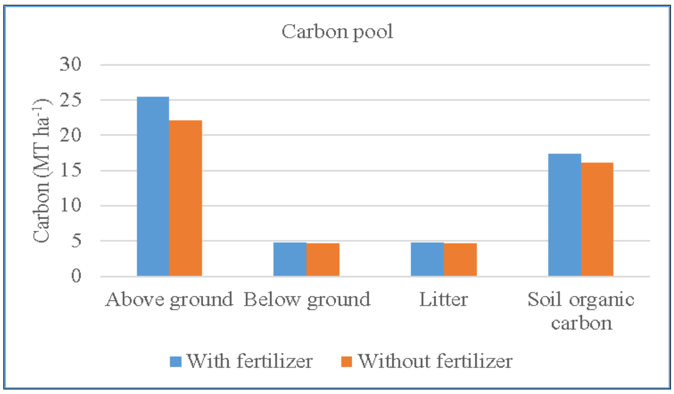

Fig. 4. Carbon sequestration potential (metric tonnes of carbon per ha) of *C. equisetifolia* plantations at harvest age in with fertilizer and without fertilizer in coastal region of Tamil Nadu, India.

paper. When pulp fiber is initially employed in paper production, it primarily consists of virgin fibers. However, in subsequent cycles, as it is repeatedly recovered and recycled, the composition shifts to include a greater proportion of recovered or recycled fiber.

The sustainability of the pulp fiber utilization cycle relies on a continuous infusion of virgin fiber. This is necessary because with each successive use, pulp fiber deteriorates and it's estimated that it can be reprocessed approximately 6 times. Additionally, around 19% of the paper we use cannot be retrieved for recycling due to its nature, such as books, documents and sanitary papers. The paper recovered and used as raw material is typically employed in the production of various paper types, including newspapers, packaging paper, corrugated cardboard, coated paper and sacks, among others. In Spain, the rate of using recovered paper, which measures the consumption of recycled paper in relation to paper production, exceeds 84%, making it the highest in Europe. The average per capita paper consumption in Europe has increased from 160 kg annually in the early nineties to the current 188 kg. During this same period, per capita paper consumption in Spain has also seen an increase, rising from 116 to 170 kg (50). Indonesia initiated a substantial pulpwood plantation program (51). This initiative was seen as a means to rapidly capture significant amounts of carbon and as an alternative to using natural resources for the domestic pulp industry. In Spain, the vast 430000 ha plantations dedicated to paper production have successfully sequestered approximately 50 million tons of carbon dioxide equivalent. These plantations, predominantly consisting of pine and Eucalyptus trees, have contributed to the sequestration of 49.85 million tons of carbon dioxide equivalent. In this investigation, the plantations of *C. equisetifolia* biomass components alone were sequestered 3.25 lakh Mt C year^{-1} in Tamil Nadu.

Carbon tables for C. equisetifolia in Tamil Nadu

The carbon table developed and presented in this present study will be of use to agencies developing projects for carbon credits under climate change programme. This study is very useful to State Forest Departments, Forest Development Corporation and Farmers of Tamil Nadu to ease their attempt in assessing the carbon sequestration potential of their plantations. A study developed biomass models to estimate the carbon stocks for hardwood tree species to develop carbon table in Spain (52).

Conclusion

Prioritizing land use options for storing carbon is essential in addressing climate change. This study demonstrates that pure plantations of *Casuarina equisetifolia* effectively store more carbon, making them a viable option for mitigating atmospheric carbon levels. Besides fulfilling the raw material demands of the paper industry, *C. equisetifolia* plantations act as significant carbon sinks within a short life cycle under proper management. Although quick harvesting of *C. equisetifolia* in 3-4 years reduces the safety span of carbon locking, paper produced from *C. equisetifolia* recycled for longer period will compensate the disadvantage of short rotation plantation as regards the permanency of locked up carbon. In the current study, it is assessed that the plantations of *C. equisetifolia* sequester 0.60 million Mt C year^{-1} in tropical regions of Tamil Nadu alone. It can be suggested that i) use of productive clones (or) at the least use of improved seed source, ii) a little wider spacing than the existing 1 m x1 m spacing, iii) optimum irrigation and fertilization and iv) increased sand proportion in soil for better nodulation and greater root expansion, will all lead to maximizing carbon sink of *C. equisetifolia* plantations. Globally, the cultivation of *C. equisetifolia* plantations offers immense potential to sequester carbon and mitigate climate change. By integrating these plantations into carbon management strategies, we can significantly contribute to global efforts to combat global warming.

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Authors' contributions

RR carried out all the field and laboratory experiments and drafted the manuscript. CB provided the technical guidelines throughout the research period and made corrections in the manuscript. SS participated in the data collection and supported in laboratory experiments.

Compliance with ethical standards

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

Ethical issues: None

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