International Journal of Ecology and Environmental Sciences 48: 229-241, 2022
ISSN: 2320-5199 (Online); https://doi.org/10.55863/ijees.2022.0114

Assessment of Carbon Stock and Carbon Sequestration Potential in Three Major Density-based Forest Ecosystems of Tripura, Northeast India

SUJIT DAS* AND SOURABH DEB
Department of Forestry & Biodiversity, Tripura University, Suryamaninagar 799022, Tripura, India
E-mail: sujit.forestry@tripurauniv.in, sdeb@tripurauniv.ac.in
***Corresponding author**

ABSTRACT
We have investigated the vegetation carbon, below ground soil carbon, C sequestration potential and soil nutrient properties of three different density-based forest ecosystems, viz., Open Forest (OF), Moderately Dense Forest (MDF) and Very Dense Forests (VDF) in Tripura, Northeast India. Tree biomass has been analyzed by the allometric protocol of Nath et al. (2019) and IPCC (2019) default manual was chosen for below ground measurement. Total biomass carbon was estimated with the manual of Brown et al. (1989). The SOC stock was analyzed by the formula of the Blanco-Canqui and Lal (2008). In this study, stand density was recorded higher in OF, while the VDF showed a higher amount of basal area. The total biomass value was estimated maximum in VDF (420.86±25.54 Mg ha^{-1}) followed by MDF (302.53±67.33 Mg ha^{-1}), and OF (186.58±35.03 Mg ha^{-1}). The C stock and Sequestration potential were also recorded higher in VDF and MDF than OF. SOC stock was observed highest in MDF followed by OF and VDF. Soil Physico-chemical properties have been showing variation along with the forest types. However, these forests have been facing a greater number of anthropogenic disturbances viz., unwanted felling, illegal smugglings of woods, and firewood gathering. We need future studies on these forest types to explore different biomass and carbon pools for restoring the forest ecosystems in the purpose of carbon sink management.

Key words: Biomass, Carbon stocks, SOC, Soil properties, Carbon sequestration potential, Forest class.

INTRODUCTION

Natural forests act as the reservoir of tropospheric CO_2 and play a driving role in regulating the unit of the earth's carbon cycle. It is a vital element in the field of carbon sequestration. In carbon inventories, it is controlling the storage and supply of carbon and assessing the driving role with carbon sequestration pools which mitigate the tropospheric CO_2 accumulation, and consequently, it is an important step for reducing the level of CO_2 productions from the world (Salunkhe et al. 2018). The studies are also crucial for developing systems for national and international carbon emission trading as well as in reducing emission from deforestation and forest degradation (REDD+) programs in developing countries (Salunkhe et al. 2018, Han et al. 2007, NEFA 2002, Kale et al. 2004). The global apprehension is that carbon management should be in forests to mitigate the increased concentration of greenhouse gases in the atmosphere (Yadav et al. 2017).

Inaccurate CO_2 emissions occur through land pattern conversion, wildfire, degradation, and many more disturbances. Recently most of the studies focusing on carbon assessment for minimizing the uncertainties related to the CO_2 emissions and their relevant cycles (Salunkhe et al. 2018). Understanding of spatial distribution of biomass is a prerequisite to finding out the sources and sinks of carbon (C) as a result of forests to degraded land and vice versa as well as their temporal variations (Salunkhe et al. 2018, Yavasli 2012).

Forest can also play a driving role in mitigating and adapting to climate change. Forests are considered sinks, sources, and reservoirs of carbon pools. Healthy and growing forests sequester and store more carbon than any other terrestrial ecosystem (FSI 2019). Carbon sequestration by forests has attracted much interest globally as it is a relatively inexpensive means of mitigating climate change. The varied topography and climate regimes, large geographical area, long coastline, and oceanic islands have endowed India with a diversity of natural biomes from deserts to alpine meadows, tropical rain forests to temperate pine forests, mangroves to coral reef and marshlands to high altitude lakes (FSI 2019). The diversity of forests in India makes it resilient to climate change and also an efficient sink of carbon (FSI 2019). India ranked eighth among the top 10 most biodiverse countries (Salunkhe et al. 2018, Butler 2016). It covered more than 73% of the forest ecosystem accomplished by tropical and subtropical forests in India (FSI 2019). However, more than 1.7 lakhs of villagers are surrounded by the community-based forest, and partially depending on forest resources. Therefore, it is very much important to assess the impacts of forest degradation on projected climate change (Salunkhe et al. 2018*)*. Due to this, carbon stock studies play a crucial role concerning develop and implement adaptation policies for biodiversity conservation, future sustainable utilization of forest resources, and reducing pressure on forest ecosystems (Kishwan et al. 2009).

According to the density of forest ecosystems as per FSI (2019), the forest of India was subdivided into three major types viz., very dense forest about 99,278 km^2 (3.02%), moderately dense forest of about 3,08,472 km^2 (9.39%), and open forest of about 3,04,499 km^2 (9.26%). The total forest cover of the country is 7,12,249 km^2, which is 21.67% of the total geographical area of the country. Currently, forest degradation is a serious concern throughout the country, which is affecting growing stock, biomass, soils and many valuable goods and ecosystem services. Though FSI has estimated forest biomass and carbon stock change but only woody growing stock was estimated as data for the other parameters were not available (FSI 2017, 2019). Therefore, based on the gap of these data records the present study was undertaken to generate information on above and belowground biomass, its distribution in the different pools (vegetation and soil), and the carbon sequestration potential of different forest class of Tripura, Northeast India (NEI).

MATERIAL AND METHODS

Description of the study sites and forest cover

This study was conducted in three major density-based forest ecosystems of Tripura, Northeast India (NEI) (Figs. 1a, b). Dense and undisturbed natural forest sites were randomly selected in the state of Tripura. The state was geographically lies between 22°56'N-24°33'N and 91°09'E-92°20'E; which covered approximately 10,486.56 km^2 of geographical area. It has been located at the Indo-Burma biodiversity hotspot (Champion and Seth 1968), which possesses enriched biodiversity. The state shares northern, southern and western international borders with Bangladesh and eastern domestic borders with Assam and Mizoram. The state has experienced tropical monsoonal, and subtropical humid climatic conditions. This area receives adequate rainfall during the monsoons (https://www.en.climate-data). The mean temperature ranges between 21°C-38°C in summer, whereas it falls up to 13°C-27°C during the winter season. The annual rainfall ranges from 1922-2855 mm (https://www.en.climate-data). As per the report of the Forest Survey of India (2019), the total forest and tree cover in the state is 7, 726 km^2 i.e., 73.68 % of the total geographical area of the state (TGA). This state has been covered by mainly five major types of forest viz., Lower bhabar sal forest, Cachar tropical evergreen forest and Moist mixed deciduous forest, Dry deciduous forest, and Dry bamboo brakes (Champion and Seth 1968). Based on the density of the forest area, the forest cover of the state has been classified in three major types: very dense forest (VDF; 657 km^2); moderately dense forest (MDF; 5,236 km^2); open forest (OF; 1,836 km^2 (FSI 2019). These forest area were dominated with some valuable woody mixed species viz., *Shorea robusta* Gaertn., *Tectona grandis* L.f., *Mimusops elengi* L., *Syzygium cumini* (L.) Skeels, *Artocarpus chaplasha* Roxb., *Dipterocarpus turbinatus* Gaertn., *Microcos paniculata* L., *Gmelina arborea* Roxb. ex Sm., *Albizia procera* (Roxb.) Benth., *Toona ciliata* M. Roem., *Bombax ceiba* L., *Mesua fera* L., *Lagerstroemia speciosa* (L.) Pers., *Terminalia bellirica* (Gaertn.) Roxb., *Microcos paniculata* L., *Holarrhena antidysenterica* (L.) Wall. ex A. DC., *Lannea coromandelica* (Houtt.) Merr., *Citrus sinensis* (L.) Osbeck, *Trema orientalis* Linn. Blume, *Swietenia mahagoni* (L.) Jacq., *Schima wallichii* (DC.) Korth., *Albizia lucida* Benth., *Antidesma* sp. along with some unwanted wild natural regenerated species. The natural hilly forest area is also the vast habitat for numerous wildlife species including Birds, Deer, Foxes, Monkeys, langur, Elephants, Wild pigs, Wild cats along with many other animals, reptiles, and vulnerable native taxa.

Sample plot design

Assessment of above ground tree biomass and vegetation survey in the density-based forest sites was carried out by ground sampling. In each forest

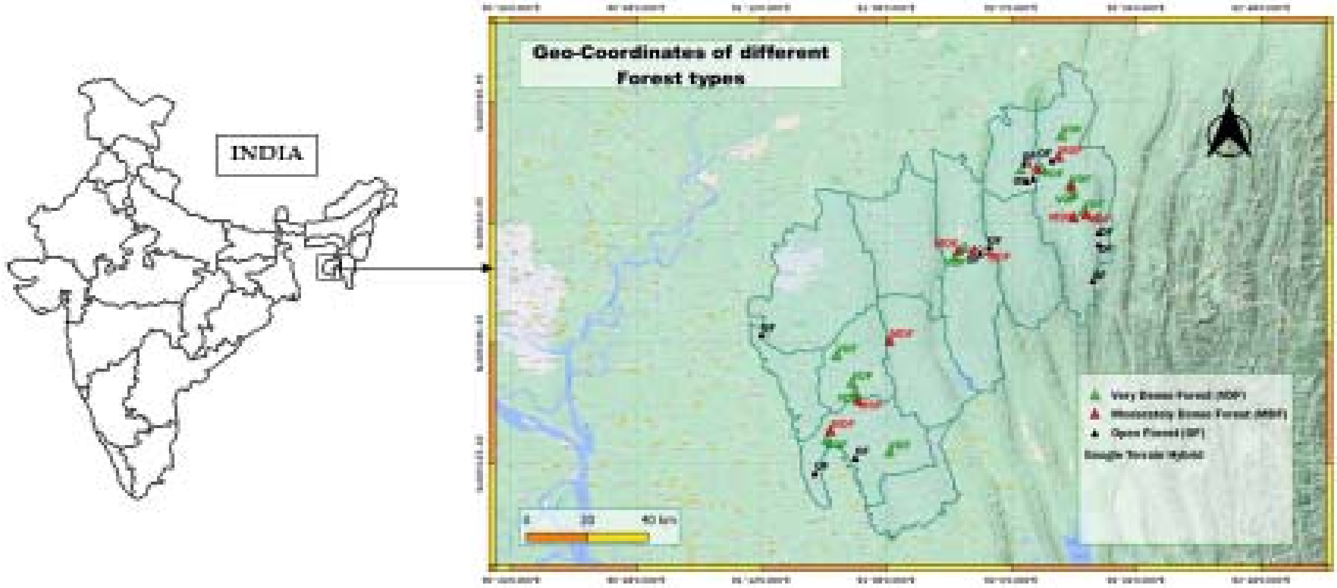

Figure 1a. Map showing the detailed geo-locations of the three different forest sampling sites in Tripura

Figure 1b. Pictures of the three different forest types of Tripura: (i) - Very dense forest (VDF); (ii) -Moderately dense forest (MDF); (iii) Open forest (OF)

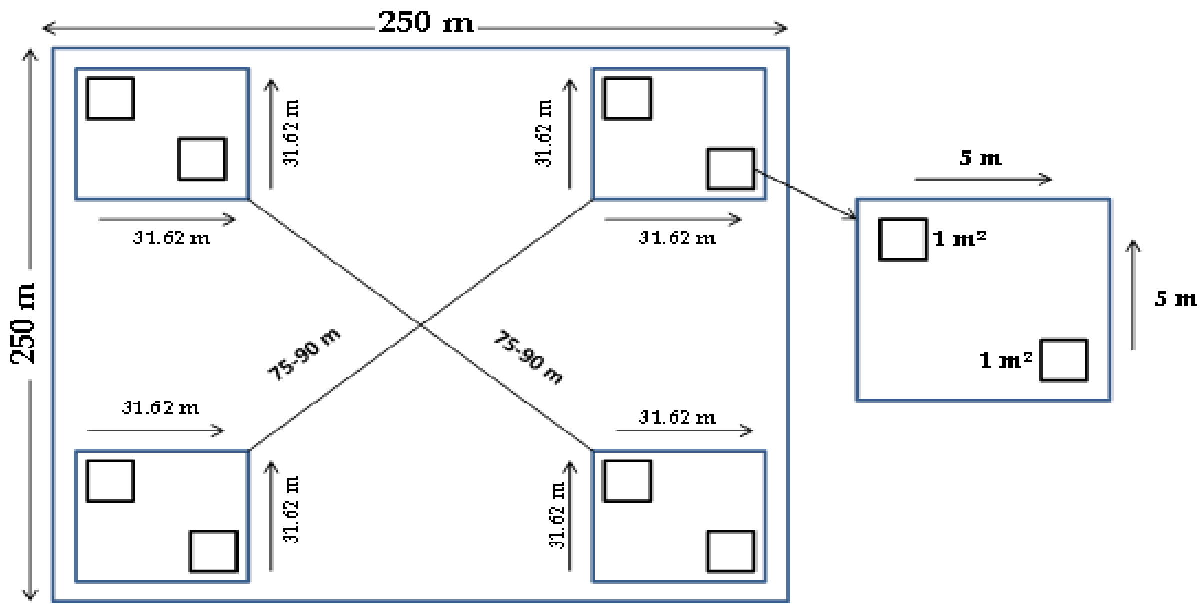

Figure 1c. Cluster sample plot design for enumerating tree-vegetation, shrubs-herbs and forest floor litter sampling (Singh and Dadhwal 2009).

type, a large quadrate of 250 m × 250 m were demarcated following ISRO-GBP/NCP-VCP protocol (Singh and Dadhwal 2009) for vegetation and soil sampling (Figure 1c). The major forest plots were selected in such a way that the effect of anthropogenic disturbance could be negligible. According to the field manual for India's "vegetation carbon pool" assessment, four nested sampling quadrats of 31.6 x 31.6 m^2 were laid in each corner respectively for covering the maximum portion of that permanent plot; which were demarcated for stand biomass estimation and forest vegetation inventory. Within each subplot, two 5 m ×5 m size quadrats were established for enumerating shrubs, and small trees (DBH ≤ 5 cm). Similarly, for herb and litter enumeration two 1 m × 1 m size quadrats were established within the shrub plots (Figure 1c). The girth of all the tree species (> 10 cm DBH) was measured at 1.37 meters above the ground.

Plant sampling and its analyses

For assessing vegetation study, the data records were collected by using randomly placed quadrate and both qualitative and quantitative methods were employed. We have collected each of the particular plant species (with its reproductive part) on a newspaper and make it as herbarium form which could be further brought to the laboratory for its identification. We have used the taxonomic book "Flora of Tripura State" (Deb 1981) for the identification of these collected species. All the tree individuals of > 10 cm diameter were tagged and their diameter at breast height (DBH) was measured at 1.37 m above the ground level. This DBH records were used to analyze the parameters like tree density and basal area.

Biomass and carbon pool estimations

A non-destructive random sampling method of assessing the biomass and C stock in tree species has been used for the present study. The above ground tree biomass (AGTB) was estimated using an allometric equation of Nath et al. (2019) whereas, the equation of IPCC (2019) default formula was used for below-ground biomass (BGB). Forest floor leaf litter biomass (LB) was determined through the phytomass formula of Ajtay et al. (1979). Understorey shrub and herb biomass were estimated by oven-dried method at 105°C. The total above ground biomass (AGB) was considered as the summation of AGTB, LB and understorey herbs-shrubs biomass; while the total biomass or TB was considered as the summing of AGB and BGB. Carbon stock was considered as 50% of the total biomass following the protocol of Brown et al. (1989). The vegetation C stock was analyzed by summing the biomass carbon of different components (AGB + BGB + understorey herbs-shrubs biomass + forest floor LB).

Soil Sampling and analysis

For soil analysis, below ground soil samples were collected from each study plot during the month of August 2017 to November 2019. Soil samples were taken from the four consecutive mini-plots of the 31.6 m^2 (0.1 ha). At each sampling location, three replicate were collected, subsamples that were mixed and homogenized to make a composite sample. Soil samples were collected using a 15 cm scaled metallic soil cores with 5.6 cm inner diameter from three consecutive soil depths viz., 0-15 cm, 15-30 cm, and 30-45 cm depths of each soil profile. For an analyses of soil samples, a total of 3 vertical profiles {(4 quadrats × 3 soil profile × 3 soil replicates × 40 sites (VDF-15/MDF-13/OF-12)} were dug which comprises a total of 1440 soil samples. Collected soil samples were placed in the plastic zipper bags and labelled in the field before brought it to the laboratory; where these samples were air-dried at room temperature (25-35°C) and then it was passed through a < 2 mm sieve to remove stones, roots, and large organic residues before analyzing physical and chemical characteristics. Soil physicochemical properties *viz*., Moisture content (MC) was determined by Blake and Hedge (1986). Bulk density (BD) was analyzed by the soil-core method (Brady and Weil 1999). Soil pH was recorded by the method of Anderson and Ingram (1993). Total Kjeldahl nitrogen (TKN) was determined through the formula of Bremmer (1996). While the Walkley and Black (1934) rapid titration method was used to determine the soil organic carbon concentration (SOC %) of each and individual soil sample. Walkley and Black process analyze 76 percent of total SOC on average (only Oxidizible C). As a result, for unrecovered organic C, a correction factor of 1.32 was used, as suggested by Walkley and Black (1934). Soil organic carbon stocks (Mg ha^{-1}) up to 1-meter soil depths were calculated by multiplying the soil volume at each horizon (m), bulk density (BD) and, soil organic carbon concentration (SOC%) by the formula of Blanco-Canqui and Lal (2008) as follows:

SOC Stock (Mg ha^{-1}) = 10^4(m^2/ha) × soil depth (m) × BD (mg m^{-3}) × SOC % /100.

Statistical analyses

Different datasheets of tree stand parameters, biomass components, soil characteristics, and their extracted tabular and graphical representations were analyzed using M.S. Excel Package-2013 (Microsoft Corporation, 2012).

RESULTS

Floristic Composition

Very dense forests (VDF)

In the case of VDF, the majority of vegetation was dominated by *Shorea robusta* and *Tectona grandis*. The species-wise description of ten major dominant tree species under a VDF ecosystem has been shown in Table 1. Among the different species in the VDF stands the maximum diameter (117.20 cm) was recorded in *S. robusta* followed by *S. wallichii* (111.53) and *T. grandis* (72.93) while the minimum value of diameter found in *M. elengi* (4.87 cm). Tree height was found highest in *S. robusta* (55 m) and lowest in *M. elengi* (10 m). The minimum and maximum above ground tree biomass (AGTB) and below ground biomass (BGB) was ranged between 0.21 to 90.90 Mg ha^{-1} and 0.06 to 26.36 Mg ha^{-1} respectively .

Moderately dense forest (MDF)

MDF are predominated by *T. grandis, S. robusta*, and *G. arborea*, among these *S. robusta* has been showing the maximum and minimum range of DBH comparison to other species. On the other hand, height was recorded maximum in *S. robusta* (53 m) followed by *A. chaplasha* (49 m) and *S. wallichii* (46 m). The maximum and minimum ranges of the above ground and below ground tree biomass were 46.91 to 0.13 Mg ha^{-1} and 25.80 to 0.07 Mg ha^{-1} respectively. The species-wise description of the ten most abundant stands in the MDF ecosystem has been shown in Table 2.

Open forest (OF)

The species-wise description of the diameter, height, and biomass of the ten most major tree species of the OF has been shown in Table 3. The most dominant species of the open forest was *T. grandis* which showing maximum diameter of 78.02 cm. It also produces 0.18 to 39.05 Mg ha^{-1} of above ground tree biomass (AGTB) and 0.05 to 11.32 Mg ha^{-1} of below ground biomass (BGB). On the other hand, height was recorded maximum in *T. grandis* (51m) *D. turbinatus* (46 m). Besides these few other important species viz., *S. wallichii*, *G. arborea*, *L. sinensis*, and *L. coromandelica* were also recorded. Few species like *S. robusta*, *A. procera*, *A. chaplasha*,

Table 1. Species wise diameter, height and biomass ranges of ten major dominant tree species in Very dense forest. DBH- Diameter at breast height; AGTB- Above ground tree biomass; BGB- Below ground biomass

Tree species	**No. of Individuals**	***DBH (Max-Min)***	***Height (Max-Min)***	***AGTB (Max-Min)***	***BGB (Max-Min)***
Artocarpus chaplasha Roxb.	40	70.31-15.92	48-14	21.16-1.71	6.13-0.49
Dipterocarpus turbinatus Gaertn.	49	48.08-17.26	38-13	16.37-1.92	4.74-0.55
Gmelina arborea Roxb. ex Sm.	9	44.26-17.13	34-17	9.58-1.37	2.78-0.39
Lannea coromandelica (Houtt.) Merr.	9	28.66-5.66	19-11	3.98-0.23	1.15-0.06
Microcos paniculata L.	13	31.01-12.48	22-11	5.14-0.79	1.49-0.23
Mimusops elengi L.	15	40.98-4.87	21-10	10.05-0.23	2.91-0.06
Schima wallichii (DC.) Korth.	30	111.53-8.15	52-12	66.05-0.43	19.15-0.12
Shorea robusta Gaertn.	160	117.2-4.90	55-11	90.90-0.21	26.36-0.06
Syzygium cumini (L.) Skeels	10	68.02-14.26	44-15	31.49-1.34	9.13-0.39
Tectona grandis L.f.	119	72.93-17.89	50-14	34.77-1.62	10.08-0.47

Table 2. Species wise diameter, height and biomass ranges of ten major dominant tree species in Moderately dense forest. DBH- Diameter at breast height; AGTB- Above ground tree biomass; BGB- Below ground biomass

Tree species	No. of Individuals	*DBH (Max-Min)*	*Height (Max-Min)*	*AGTB (Max-Min)*	*BGB (Max-Min)*
Artocarpus chaplasha Roxb.	14	65.09-15.57	49-15	19.49-0.98	10.72-0.54
Delonix regia (Hook.) Raf.	5	44.90-25.15	33-19	9.03-4.27	4.96-2.35
Gmelina arborea Roxb. ex Sm.	34	32.45-11.33	22-13	4.06-0.60	2.23-0.33
Lannea coromandelica (Houtt.) Merr.	12	37.77-9.52	26-11	7.62-0.69	4.19-0.38
Microcos paniculata L.	13	29.33-9.07	19-12	4.32-0.52	2.38-0.29
Mimusops elengi L.	12	29.29-10.73	24-12	6.07-0.99	3.34-0.54
Schima wallichii (DC.) Korth.	16	59.58-17.80	46-16	23.52-1.74	12.94-0.95
Shorea robusta Gaertn.	105	76.81-3.56	53-11	46.91-0.13	25.80-0.07
Tectona grandis L.f.	200	65.31-4.87	45-10	27.68-0.17	15.22-0.09
Terminalia bellirica (Gaertn.) Roxb.	7	32.22-9.74	22-14	6.08-0.62	3.34-0.34

Table 3. Species wise diameter, height and biomass ranges of ten major dominant tree species in Open forest. DBH- Diameter at breast height; AGTB- Above ground tree biomass; BGB- Below ground biomass

Tree species	No. of Individuals	*DBH (Max-Min)*	*Height (Max-Min)*	*AGTB (Max-Min)*	*BGB (Max-Min)*
Albizia lucida Benth.	10	34.20-18.47	22-15	7.50-2.23	2.17-0.64
Areca catechu L.	141	56.75-7.42	44-11	15.92-0.27	4.61-0.08
Citrus sinensis (L.) Osbeck	12	20.44-13.21	17-14	2.75-1.23	0.79-0.35
Dipterocarpus turbinatus Gaertn.	22	58.91-23.28	46-18	25.62-3.14	7.43-0.91
Gmelina arborea Roxb. ex Sm.	17	54.23-16.43	35-14	13.28-1.17	3.85-0.34
Lannea coromandelica (Houtt.) Merr.	13	28.02-6.46	22-10.1	3.85-0.26	1.11-0.07
Litchi chinensis Sonn.	13	28.18-13.50	28-15	7.01-1.45	2.03-0.42
Schima wallichii (DC.) Korth.	23	35.50-12.54	39-13	8.75-0.88	2.53-0.25
Tectona grandis L.f.	129	78.02-4.90	51-10	39.05-0.18	11.32-0.05
Terminalia bellirica (Gaertn.) Roxb.	12	22.61-4.87	25-10.2	3.93-0.19	1.14-0.05

G. arborea, *L. coromandelica*, *M. paniculata*, *M. elengi*, *S. wallichii*, *T. grandis*, and *T. bellirica* were also found in all the sites.

Different biomass pools and their C stocks across the forest types

Among the three forest classes OF showed the highest mean tree density of 370 ± 35.31 stands ha^{-1} (Table 4). Similar trend have also been observed for the tree density in MDF of the region. It showed an average tree density of 353.08 ± 25.95 trees ha^{-1} while a VDF showed an average tree density of 335.33 ± 27.75 trees ha^{-1}. Among the forest classes, the VDF had a mean basal area of 14.90 ± 0.31 m^2 ha^{-1}. While the average basal area of MDF and OF types were 9.26 ± 0.23 m^2 ha^{-1} and 5.96 ± 0.16 m^2 ha^{-1} respectively. The average total biomass stock (above ground + below ground) was recorded maximum (420.86 Mg ha^{-1}) in the VDF; while the minimum in OF (186.58 Mg ha^{-1}). The mean vegetation carbon stock (above ground + below ground C) was also found highest (210.43 Mg ha^{-1}) in VDF followed by MDF (151.26 Mg ha^{-1}) and OF (93.29 Mg ha^{-1}) (Table 4; Figure 2). Among the forest types, mean SOC stock was recorded in the order of MDF (168.91 Mg ha^{-1}) > OF (144.92 Mg ha^{-1}) > VDF (132.25 Mg ha^{-1}). So, the overall results indicate that the VDF showing driving role in the vegetational biomass and carbon stock maintenance; while the below ground SOC stock was found maximum in OF (Table 4).

Sequestration potential of different forest ecosystem

Biomass and soil carbon sequestration for different kinds of density-based diverse forest class in Tripura are represented in Figure 2. Among the different

Table 4. Different biomass and carbon pool storages under the major forest types. VDF- Very dense forest; MDF- Moderately dense forest; OF- Open forest; AGB- Above ground biomass; BGB- Below ground biomass; TB- Total biomass; AGC- Above ground carbon; BGC- Below ground carbon; VC- Vegetation carbon; SOC- Soil organic carbon; (±) - Standard error of mean.

Components/Forest types	***VDF***	***MDF***	***OF***
Stand density (Nos ha^{-1})	335.33 ±27.75	353.08±25.95	370.0 ±35.31
Basal area (m^2 ha^{-1})	14.90± 0.31	9.26±0.23	5.96± 0.16
AGB (Mg ha^{-1})	326.24±39.61	234.52±52.19	144.63±27.15
BGB (Mg ha^{-1})	94.61±11.49	68.01±15.13	41.94± 7.87
TB (Mg ha^{-1})	420.86±25.54	302.53±67.33	186.58±35.03
AGC (Mg ha^{-1})	163.13±19.80	117.26±26.09	72.32±13.57
BGC (Mg ha^{-1})	47.31± 5.74	34.01±7.56	20.97± 3.93
VC (Mg ha^{-1})	210.43 ±25.54	151.26±33.66	93.29±17.51
SOC stock (Mg ha^{-1})	132.25± 7.00	168.91±12.20	144.92±7.66

Table 5. Soil Physico-Chemical properties in forest ecosystems of Tripura. SD- Soil depths; MC- Moisture content; BD- Bulk density; SOC- Soil organic carbon; TKN- Total Kjeldahl nitrogen; VDF- Very dense forest; MDF- Moderately dense forest; OF- Open forest; (±) = Standard error of mean.

Forest types	**SD (cm)**	***MC %***	***BD (mg m^{-3})***	***pH***	***SOC %***	***TKN %***
	0-15	18.32±0.82	1.67±0.13	5.76±0.44	1.48±0.69	0.18±0.02
VDF	15-30	18.57±0.75	1.40.±0.19	5.33±0.16	1.37±0.46	0.15±0.02
	30-45	18.11±0.72	1.31±0.11	5.59±0.07	1.29±0.38	0.11±0.03
	0-15	21.88 ± 1.69	1.80±0.13	5.65±0.32	1.80 ±0.30	0.12 ± 0.01
MDF	15-30	20.73± 1.79	1.81±0.12	5.59±0.11	1.98 ±0.06	0.12 ± 0.01
	30-45	20.64 ± 2.53	1.88±0.10	5.43±0.06	1.62 ±0.12	0.10 ± 0.01
	0-15	23.23±0.71	1.51 ±0.27	5.76±0.44	1.19 ±0.16	0.10 ±0.02
OF	15-30	22.37±0.60	1.52 ±0.12	5.33±0.16	1.41 ±0.16	0.08± 0.01
	30-45	21.24±0.47	1.29 ±0.05	5.59±0.07	1.11 ±0.06	0.09 ±0.01

forest categories, VDF exhibited the highest rate of vegetation C sequestration (5.93±0.98) followed by MDF (3.72±1.37 Mg ha^{-1} yr^{-1}), and OF class (2.33±0.59 Mg ha^{-1} yr^{-1}). Similarly, SOC sequestration rate was highest under VDF (3.45±0.36 Mg ha^{-1} yr^{-1}) followed by MDF (2.38±0.24 Mg ha^{-1} yr^{-1}) and OF (1.76±0.14 Mg ha^{-1} yr^{-1}).

It was observed from the carbon sequestration rate of forest ecosystems, the highest sequestration rate (%) of above ground stock was recorded in the VDF ecosystem (2.53%) followed by OF (2.25%) and the lowest in MDF with the sequestration rate of 2.21% (Fig. 3).

Below ground SOC stock (Mg ha^{-1}) under different forest class were recorded and showed in Figure 4. It was observed that the highest amount of SOC stock was shown a significant and decreasing trend across the soil depths in almost all the forest types. In a VDF ecosystem, the highest SOC stock was 49.99 Mg ha^{-1} recorded under the depth of 0-15 cm; while the lowest stock was found in 30-45 cm depth (38.09 Mg ha^{-1}). Similarly, In the case of MDF ecosystem, the highest stock of SOC was 67.69 Mg ha^{-1} recorded in the upper soil depth; while the lowest stock was observed under 30-45 cm depth (48.25 Mg ha^{-1}). On the other hand, in OF the highest value of SOC Stock was 62.25 Mg ha^{-1} found in the top-most soil profile followed by 49.94 Mg ha^{-1} in 15-30 cm and 31.73 Mg ha^{-1} in 30-45 cm.

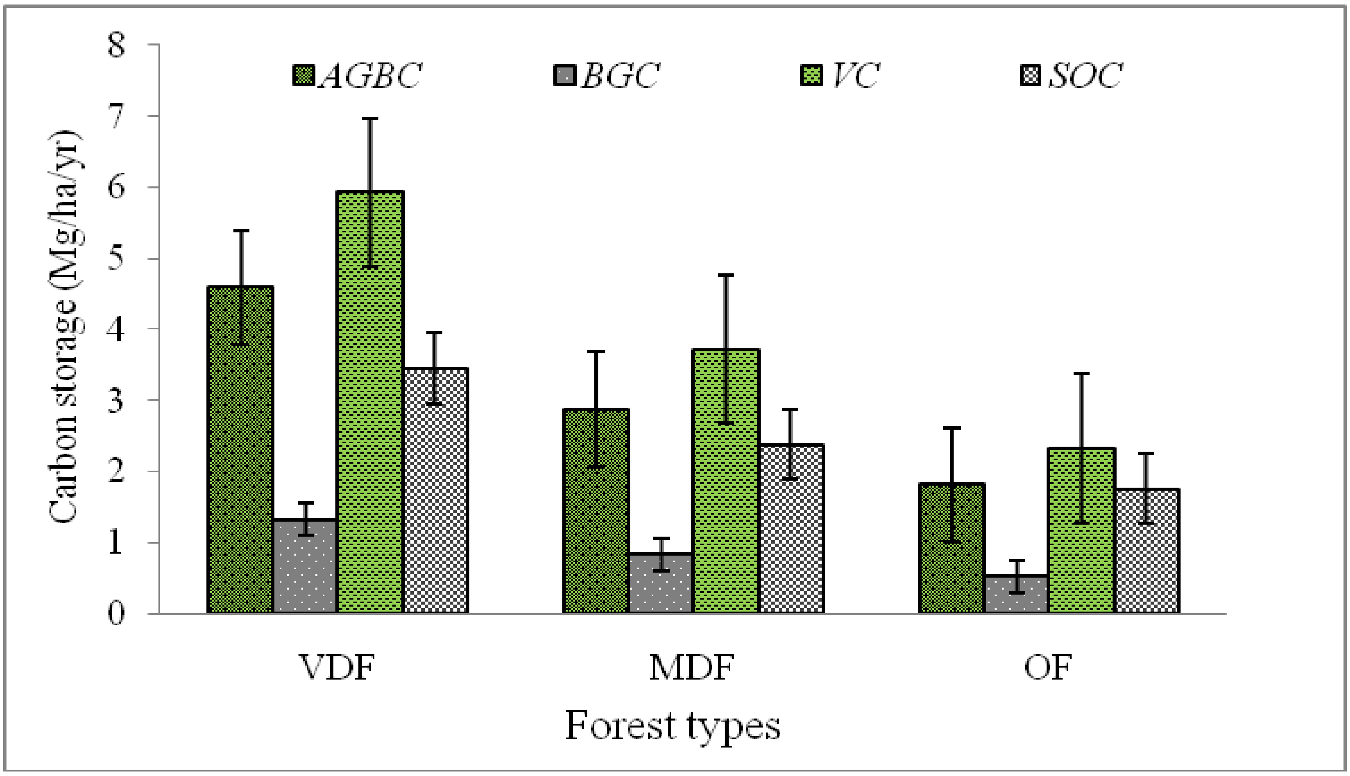

Figure 2. Biomass and soil carbon sequestration for different kinds of density based diverse forest of Tripura. VDF- Very dense forest; MDF- Moderately dense forest; OF- Open forest; AGBC- Above ground biomass carbon; BGBC- Below ground biomass carbon; VC- Vegetation carbon; SOC- Soil organic carbon

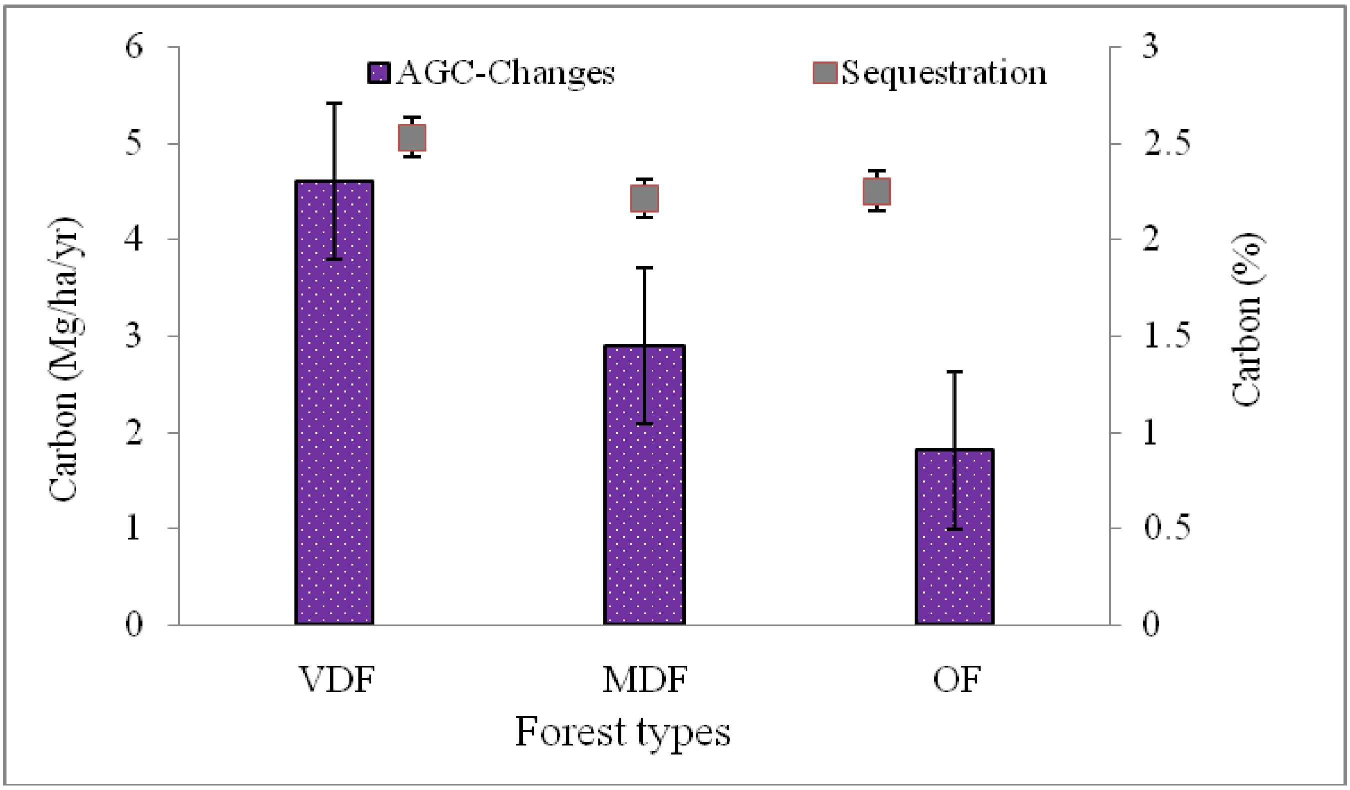

Figure 3. Trend of Rate of Carbon Sequestration (%) across the different forest ecosystems of Tripura. VDF- Very dense forest; MDF- Moderately dense forest; OF- Open forest; AGC- Above ground carbon

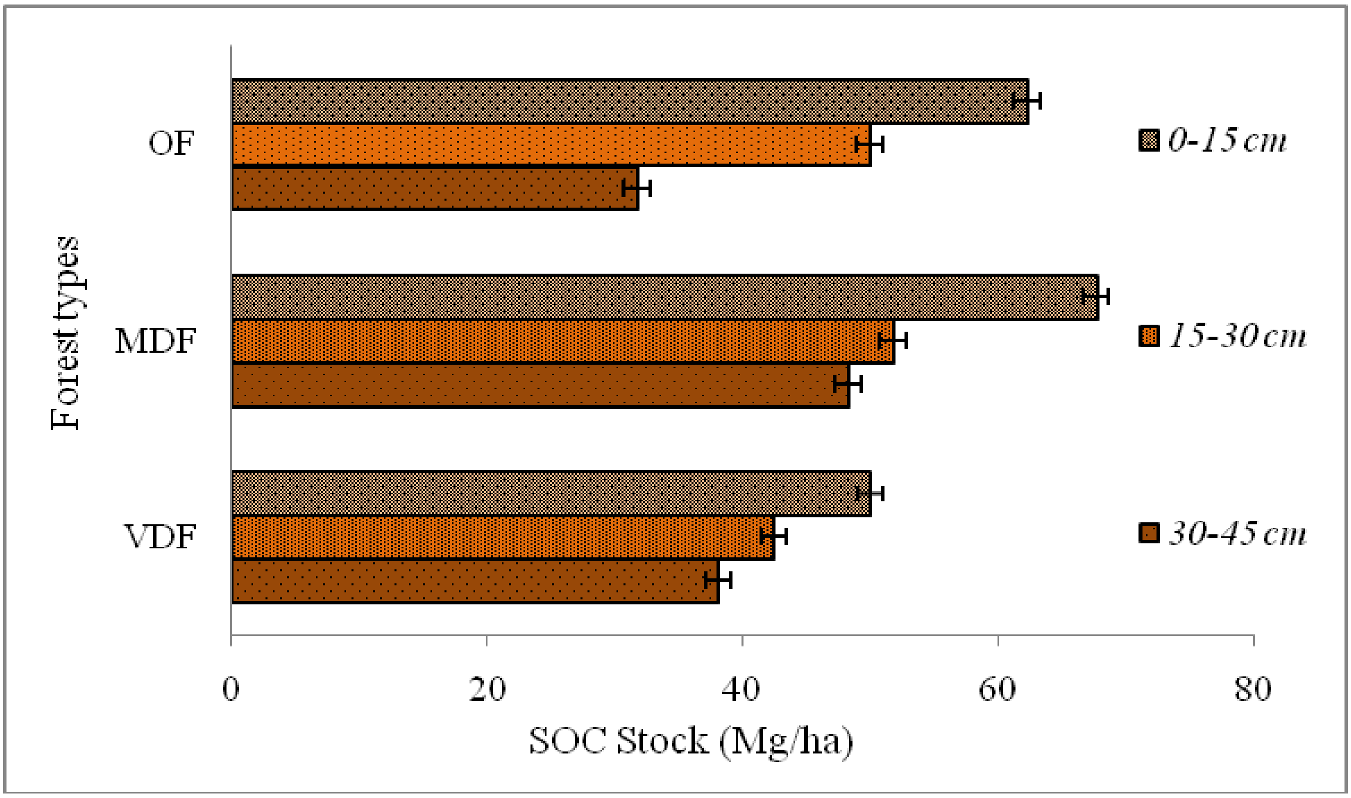

Figure 4. Depth-wise distribution of SOC Stocks (Mg ha^{-1}) in different forest types of Tripura. VDF- Very dense forest; MDF- Moderately dense forest; OF- Open forest

Soil parameters

Soil Physico-chemical parameters indicate that higher moisture content was recorded in OF compared to other forest stands and ranged between 21.24% to 23.23% (Table 5). Whereas, VDF showed lowest moisture content of 18.11% in the depth of 30-45 cm. The soil bulk density of the present study was varied between 1.29 to 1.88 mg m^{-3}. The highest bulk density was found in MDF in the depth of 30-45 cm (1.88 mg m^{-3}); while, the lowest bulk density was recorded in the OF (1.29 mg m^{-3}). In the present study, the soil pH was ranged between 5.33 to 5.76. The maximum pH was recorded in VDF at 0-15 cm depth and the minimum one in OF in the depth of 30-45 cm.

The value of soil organic carbon concentration (%) has fluctuated across all depth classes. Highest organic carbon concentration (1.98%) was recorded in MDF at 15-30 cm depth and the lowest in OF (1.11%) at the depth of 30-45 cm. A decreasing trend of total nitrogen was observed from upper to lower soil depths. The average value of nitrogen was mostly observed higher in the upper-most soil layers in all the forest stands. The highest total nitrogen value (0.18%) was recorded in VDF at 0-15 cm soil depth while the lowest (0.08%) value was recorded in the OF at the depth of 15-30 cm.

DISCUSSION

The present study revealed that among the three forest class (OF, MDF, and VDF), stand density was lowest in VDF and vegetation was dominated by *S. robusta*, *T. grandis* and *S. wallichii*. Among them, *S. robusta* has been showing higher stocks in tree parameters. The maximum diameter of 117.20 cm and tree height of 55 meters was recorded in *S. robusta*. The above ground tree biomass (AGTB) and below ground biomass (BGB) were ranged between 0.21 to 90.90 Mg ha^{-1} and 0.06 to 26.36 Mg ha^{-1} respectively in *S. robusta*. MDF types are predominated by *T. grandis*, *S. robusta*, and *G. arborea*; whereas the most dominant species of the OF is *T. grandis*. In OF, the total AGB and BGB ranged from 0.18 to 39.05 Mg ha^{-1} and 0.05 to 11.32 Mg ha^{-1}, respectively. Besides these few other important species like *S. wallichii*, *D. turbinatus, G. arborea, L. sinensis*, and *L. coromandelica* were also observed. Few species like *S. robusta*, *T. grandis*, *A. procera*, *A. chaplasha*, *G. arborea*, *L. coromandelica*, *M. paniculata*, *M. elengi*, *S. wallichii* and *T. bellirica* were the common tree species found in all the forest class. However, these forests have been facing a greater number of anthropogenic disturbances viz., unwanted felling, illegal smugglings of woods, and firewood gathering, which decreases the species number and its richness to the wild day-by-day.

The highest tree density was recorded under OF (370±35.31 stands ha^{-1}), whereas the maximum basal area of the stands was estimated in VDF with a value of 14.90±0.31 m^2 ha^{-1}. Stand density and basal area for tree species in our present study were much lower compared to the reported values of the three major disturbed Banj Oak forest of Central Himalaya (Pandey et al. 2020), and the Natural forest ecosystem of Barak valley, Assam (Nandy and Das 2013). Stand density for tree species in the recent study was too high than the reported value of highly disturbed sites, but much lower than the least disturbed & mild disturbed sites of the Tropical Wet Evergreen Rainforest of Eastern Himalaya (Gogoi et al. 2017). Basal area was recorded much lower to the values of three disturbed forest regimes of the Tropical Rainforest of Eastern Himalaya (Gogoi et al. 2017). Fewer species numbers and the lower diversity patches in our study plots might be the factors for this lower value. Along with this illegal cutting of big trees for fuelwood, cash crop plantation and timber is another major problem of the sites. Regeneration of more varieties has been the need for the betterment of species richness in the study sites. The management strategies should be needed for planting different mixed species, which could be improving the tree richness and reducing the anthropogenic disturbances from the sites.

In this study, the mean average of AGB (326.24±39.61Mg ha^{-1}) and BGB (94.61±11.49 Mg ha^{-1}) were recorded maximum in VDF, and the value is higher compared to the stock of the Tropical Wet Evergreen forest of Eastern Himalaya (Gogoi et al. 2017). These AGB and BGB values are also much higher than the earlier reported value of Tripura (FSI 2019), tropical Tarai hill forest of Shivaliks (Adhikari et al. 2020), and Tropical semi-evergreen and deciduous forest ecosystems of India (Swami 1989); but substantially much lower than the undisturbed and moderately disturbed sites of that particular tropical Banj Oak forest (Pandey et al. 2020), the study of Garhwal Himalaya (Sheikh et al. 2020), and reported values of Negi et al. (1990) in tropical forest ecosystem of Tripura. On an average, the total biomass value (TB) was estimated highest in VDF (420.86±25.54 Mg ha^{-1}) followed by MDF (302.53±67.33 Mg ha^{-1}), and OF (186.58±35.03 Mg ha^{-1}). Whereas total carbon stock was in the order of VDF (210.43 ±25.54 Mg ha^{-1}) > MDF (151.26±33.66 Mg ha^{-1}) > OF (93.29±17.51 Mg ha^{-1}). These values were significantly lower than the earlier reported value of Gogoi et al. (2017) in a tropical wet-evergreen rainforest. These total biomass values were also quite higher than the value of tropical highly disturbed Banj Oak forests of Central Himalaya; but substantially much lower than the undisturbed and moderately disturbed sites of that particular tropical Banj Oak forest (Pandey et al. 2019). Extensive and frequent tree clearance for commercial and traditional needs results in reducing the production of biomass and carbon storage in the forest ecosystem day by day. Total soil organic carbon stock (0-45 cm) was recorded in the order of MDF (168.91 Mg ha^{-1})> OF (144.92 Mg ha^{-1})>VDF (132.24 Mg ha^{-1}). These values were significantly much higher than the total SOC stock values of Gogoi et al. (2017) in Eastern Himalaya, but comparatively similar with five different types of plantation forest ecosystems of Tripura (Choudhary et al. 2019). Higher SOC stocks in MDF due to higher deposition of organic matter across the soil surfaces on behalf of above-ground foliages input.

In C-sequestration potential, forest ecosystems play a vital role. In our present study, the highest stock of C-sequestration of total biomass pool was recorded under VDF (5.93 Mg ha^{-1} yr^{-1}) followed by MDF (3.72 Mg ha^{-1} yr^{-1}), and OF (2.33 Mg ha^{-1} yr^{-1}). The study also reported that the percentage of sequestration rate of above-ground carbon stock was recorded highest in VDF (2.53%) followed by OF (2.25%) and MDF (2.21%). These values were significantly lower than the earlier reported value of Gogoi et al. (2017) in the tropical wet-evergreen rainforest, but quite similar to the values recorded by Pandey et al. (2020) in the major disturbed Banj Oak forests of Central Himalaya. Soil organic carbon sequestration (up to 45 cm) was also recorded in the order of VDF (3.45 Mg ha^{-1} yr^{-1}) followed by MDF (2.38 Mg ha^{-1} yr^{-1}), and OF (1.76 Mg ha^{-1} yr^{-1}). These values were also significantly much higher than the earlier reported values of Gogoi et al. (2017) in the Eastern Himalaya.

In our study, the depth-wise distribution of the SOC stock in 0-45 cm was reported maximum in MDF (67.69 Mg ha^{-1}) in the upper soil depth, while the minimum stock was found under VDF (38.09 Mg ha^{-1}) across the 30-45 cm of soil depths. These SOC stocks (Mg ha^{-1}) values were quite similar to the earlier reported mean value of Tripura (FSI 2019, Choudhary et al. 2019). On the other hand, the present value is also much higher than the earlier values of Pandey et al. (2020) in the Banj Oak forests of Central Himalaya. The adding of higher leaf-litter fall on the forest floor under these forest ecosystems boosts up the microbial activities, and rich humus deposition across the soil profiles is likely an important key factor for increased soil carbon.

Soil moisture content (%) has been shown a significant increasing trend across the depths and ranged from 18.11 to 23.33%, which is higher than the mean percent value of Choudhary et al. (2019) in the natural forest ecosystem of Tripura, but quite similar with the study of Mapoong and Tripathi (2019) in the Natural forest of Mizoram. The highest moisture content was recorded under OF, while the VDF showing the lowest amount of moisture across the soil profiles. The enriched soil moisture content indicates that the amount of water present due to sufficient litter decomposition in upper-most soil layers, which would maintain the water content during monsoon and stored for the dry session, and serves as transport of plant nutrients, regulates soil temperature, balanced the health of soil microbes. The low moisture content found in this study could be attributable to the poor humus deposition in soil upper surfaces which do not properly maintain the water storage during hot summer and dry season. In our present study, the mean bulk density ranged between 1.29 to 1.88 mg m^{-3}, which was roughly higher (0.74 to 1.22 mg m^{-3}) than the mean values of the three disturbance sites of Central Himalaya (Pandey et al. 2020). The bulk density value of the present study was comparatively high than the value of Choudhury et al. (2019).The highest value was recorded under MDF, while the OF showing the lowest amount of bulk density across the soil profiles. This higher bulk density indicates the minimum porosity and soil compactness across the sites. It may resulted a restriction to the below ground root-rhizomes growth, less soil moisture, and insufficient air and water movement across the soil-layers. In the present study, the soil pH ranged between 5.33 to 5.76, which falls under moderate acidic in scale. Our estimated values are comparatively higher than the earlier recorded value of Choudhary et al. (2019) in the Natural forest site of Tripura, North-east India. This value is also comparatively higher than the earlier reported value of Shimrah et al. (2015) in the Natural forest site of Domong village landscape. The highest pH value has been reported under a VDF and the lowest one in the OF ecosystem. In our study, the soil was showed as acidic, which could be the enriched forest floor which potentially increases the decomposition activities and maintain adequate organic residues for greater microbial activities.

In our study, the SOC% has fluctuated across all depth classes, and it was showing the maximum SOC concentration of 1.98% in MDF at 15-30 cm depth, whereas the OF has been showing the minimum value (1.11%) across the 30-45 cm of soil-layer. Our estimated value is comparatively much lower than the earlier reported value of Shimrah et al. (2015) in the natural forest site of both the Domong and Yogong village landscape in Arunachal Pradesh, North-East India. This value is also comparatively higher than the earlier recorded value of Choudhury et al (2019) in the five plantation forests of Tripura, NE-India and Mapoong and Tripathi (2019) in Natural forest ecosystem of Mizoram. The upper and middle-most soil profiles were showing higher organic storage compared to lower soil profiles. It could be due to the higher deposition of organic content and decomposed residues in the upper soil layer, which provides an adequate amount of organic carbon and vital nutrients for improving soil health. Total nitrogen (%) has been shown a significant decreasing trend across the depths and ranged between 0.08 to 0.18%, which was lower than the value reported by Mapoong and Tripathi (2019). Our recorded values were also much lower than the values of Shimrah et al. (2015) in the natural forest site of Arunachal Pradesh, which was showing nitrogen concentration of 0.15 to 0.31%. The maximum nitrogen value was recorded under VDF at 0-15 cm soil depth, while the OF showed the minimum amount of nitrogen concentration at 15-30 cm soil depth. The enriched nitrogen concentration indicates the presence of good amount of water due to higher litter decomposition in the uppermost soil layers of the study sites.

CONCLUSIONS

The current study has revealed that the most predominant species in different density-based forest ecosystems are *S. robusta*, *T. grandis*, and *G. arborea*. Among the three forest class, the stand density was recorded highest in OF, while the VDF showed maximum basal area. Total biomass and total C-stocks were recorded in the order of VDF>MDF>OF. Below-ground SOC stocks were showing higher dominance in MDF. Sequestration potential was recorded as highest in VDF and lowest in OF. In soil Physico-chemical properties, the VDF was showed the highest nitrogen and pH levels, whereas MDF showed higher bulk density and SOC%. While OF has been showing a higher amount of moisture content across the soil profiles. Biomass-C and Sequestration potential was recorded higher in VDF and MDF than OF. Soil Physico-chemical properties have been showing variations along with the forest class. However, these forests have been facing a greater number of anthropogenic disturbances viz., unwanted felling, illegal smugglings of woods, and firewood gathering, which decreases the species number and its richness to the wild day-by-day. Unwanted-frequent tree clearance results in reduced tree numbers and its associated physiological parameters. All these negative factors have brought up a great degradation risk on the forest ecosystems of a particular area. The study underlines the importance of restoration of open and degraded forest to enhance their soil quality and carbon stock. So, the conservation of these forests will help to maintain the ecological cycles and storing of the different regional biomass and carbon pools. We suggest more future studies on these forest class to explore different biomass pools and carbon stocks to represent the ecosystem carbon stock and restore such systems for better understanding their role in carbon sink management.

ACKNOWLEDGEMENTS

We sincerely acknowledge the different forest range offices for serving their helping hands during the field selection. We also thank to our former lab member Mr. Biswajit Das for helping us during the field sampling. Authors deeply acknowledged the Department of Science and Technology (DST), New Delhi (Sanctioned No. GOI (DST/CCP/MRDP/190/2019(G)-NMSHE)) for proving funding assistance of this work.

Authors' contribution: Sujit Das (SD) and Sourabh Deb (SRD) jointly formulated the research work. SD has conducted the field and lab experiments and with SRD performed data analysis. Both the authors contributed to the final draft and approved the manuscript.

Conficts of Interest: The authors declare that they have no competing interests.

REFERENCES

Adhikari, B., Lodhiyal, N. and Lodhiyal, L.S. 2020. Assessment of crop yield productivity and carbon sequestration in agroforestry systems in Central Himalaya, India. Agroforestry Systems, 94(1), 281-296.

Ajtay, G.L., Ketner, P. and Duvigneaud, P. 1979. Terrestrial primary production and phytomass. pp. 129-182. In: The Global Carbon Cycle Bolin, B., Degens, E., Kempe, S. and Ketner, P. (Eds.), SCOPE edition. 13, John Wiley, Chichester.

Anderson, J.M. and Ingram, J.S.I. 1993. Tropical Soil Biology and Fertility: A Handbook of Methods, 2nd eds. C.A.B. International. Wallingford, UK.

Banik, B., Deb, D., Deb, S. and Datta, B.K. 2018. Assessment of Biomass and Carbon Stock in Sal (*Shorea robusta* Gaertn.) Forests under Two Management Regimes in Tripura, Northeast India. Journal of Forest and Environmental Science, 34(3), 209-223.

Bhuyan, P., Khan, M.L. and Tripathi, R.S. 2003. Tree diversity and population structure in undisturbed and human-impacted stands of tropical wet evergreen forest in Arunachal Pradesh, Eastern Himalayas, India. Biodiversity and Conservation, 12, 1753-1773.

Blacke, G.R. and Hedge, K.H. 1986. Bulk Density. In: Klute, A. (Eds).Methods of soil analysis, part-I, 2nd edition, Agron Monograph, ASA and SSSA, Madison. WI, 363-375.

Blanco-Canqui, H. and Lal, R. 2008. No-tillage and soil-profile carbon sequestration: an on-farm assessment. Soil Science Society of America Journal, 72, 693-701.

Brady, C.N. and Weil, R.R. 1999. The Nature and Properties of Soils, 12th Ed., Macmillan Publishing Co., New York. 881pp.

Bremmer, J.M. 1996. Nitrogen Total. pp. 1085-1122. In: Sparks, D.L. (Ed.), Methods of Soil Analysis Part 3: Chemical

Methods, SSSA Book Series 5, Soil Science Society of America, Madison. Wisconsin.

Brown, S., Gillespie, A.J. and Lugo, A.E. 1989. Biomass estimation methods for tropical forests with applications to forest inventory data. Forest Science, 35(4), 881-902.

Champion, H.G. and Seth, S.K. 1968. (Reprinted 2005) A revised survey of the forest types of India. Natraj Publishers, Dehradun, 404pp.

Choudhury, B.K., Majumdar, K. and Datta, B.K. 2016. Carbon Sequestration Potential and Edaphic Properties along the Plantation Age of Rubber in Tripura, Northeastern India. Current World Environment, 11(3), 756-766.

Choudhary, B.K., Majumdar, K. and Datta, B.K. 2019. Potential Biomass Pools and Edaphic Properties of Plantation Forest in Tripura, India. International Journal of Ecology and Environmental Sciences, 45(4), 369-381.

Deb, D.B. 1981. The Flora of Tripura State. Vol. 1. Today and Tomorrow's Printers and Publishers, New Delhi.

Devi, L.S. and Yadava, P.S. 2006. Floristic diversity assessment and vegetation analysis of tropical semi-evergreen forest of Manipur, north east India. Tropical Ecology, 47 (1), 89-98.

FSI. 2017. India State of Forest Report 2017. Forest Survey of India, Ministry of Environment and Forests. Dehradun.

FSI. 2019. Carbon Stock in India's Forests India. State of Forest Report 2019 Vol 1. Retrieved April, 2020.

Gogoi, A., Sahoo, U.K. and Singh, S.L. 2017. Assessment of biomass and total carbon stock in a tropical wet evergreen rainforest of Eastern Himalaya along a disturbance gradient. Journal of Plant Biology and Soil Health, 4(1), 1-8.

Han, F.X., Plodinec, M.J., Su, Y., Monts, D.L. and Li, Z. 2007. Terrestrial carbon pools in southeast and South-Central United States. Climate Change, 84, 191-202.

Kanime, N., Kaushal, R., Tewari, S.K., Raverkar, K.P., Chaturvedi, S. and Chaturvedi, O.P. 2013. Biomass production and carbon sequestration in different tree-based systems of Central Himalayan Tarai region, Forests, Trees and Livelihoods, 22(1), 38-50.

Kishwan, J. Pandey, R. and Dadhwal, V.K. 2009. India's Forest and Tree Cover: Contribution as a Carbon Sink. 130 ICFRE BL-23. ICFRE, Dehradun.

Kale, M., Singh, S., Roy, P.S., Deosthali, V. and Ghole, V.S. 2004. Biomass equations of dominant species of dry deciduous forest in Shivpuri district, Madhya Pradesh. Curr Sci, 87(5), 683-687.

Mapoong, C. and Tripathi, S.K. 2019. Soil properties under different land use systems of Mizoram, North East India. Journal of Applied and Natural Science, 11(1), 121-125.

Nandy, S. and Das, A.K. 2013.Comparing tree diversity and population structure between a traditional agroforestry systems and natural forests of Barak Valley, Northeast India. International Journal of Biodiversity Science and Ecosystem Services Management, 9(2), 104-113.

Nath, A.J., Tiwari, B.K., Silesh, G.W., Sahoo, U.K., Brahma, B., Deb, S., Devi, N.B., Das, A.K., Reang, D., Chaturvedi, S.S., Tripathi, O.P., Das, D.J. and Gupta, A. 2019. Allometric Models for Estimation of Forest Biomass in North East India. Forestry, 10, 103.

NEFA. 2002. North East State Forest Association. Carbon sequestration and its impacts on forest management in the northeast.

Negi, J.D.S., Bahuguna, V.K. and Sharma, D.C. 1990. Biomass production and distribution of nutrients in 20 years old teak (*Tectona grandis*) and gamar (*Gmelina arborea*) plantation in Tripura. Indian Forester, 116, 681-686.

Pandey, A., Arunachalam, K., Thadani, R. and Singh, V. 2020. Forest degradation impacts on carbon stocks, tree density and regeneration status in banj oak forests of Central Himalaya. Ecological Research, 35, 208-211.

Salunkhe, O., Khare, P.K., Kumari, R. and Khan, M.L. 2018. A systematic review on the aboveground biomass and carbon stocks of Indian forest ecosystems. Ecological Processes, 7, 17.

Singh, S. and Dadhwal, V.K. 2009. Manual on spatial assessment of vegetation carbon pool of India. Indian Institute of Remote Sensing (National Remote Sensing Centre), ISRO, Government of India. Dehradun. 1-32.

Sheikh, M.A., Kumar, M., Todaria, N.P. and Pandey, R. 2020. Biomass and soil carbon along altitudinal gradients in temperate Cedrus deodara forests in Central Himalaya, India: Implications for climate change mitigation. Ecological Indicators, 111, 106025.

Shimrah, T., Rao, K.S. and Saxena, K.G. 2015. Soil Property Variations Under Different Land Use/ Cover Types In Traditional Agricultural Landscape In Northeast India. Journal of Chemistry, Environmental Sciences and its Applications, 2(1), 73-97.

Swami, H.R. 1989. Study of organic productivity, nutrient cycling and small water shade hydrology in natural forests and in monoculture plantations in Chikmagalur district, Karnataka, Final paper, Sri Jagadguru Chandrashekhara Bharti Memorial College, Sringeri, India.

Tolangay, D. and Moktan, S. 2020. Trend of studies on carbon sequestration dynamics in the Himalaya hotspot region: A review. Journal of Applied and Natural Science, 12(4), 647-660.

Walkley, A. and Black, I.A. 1934. An examination of Degtjareff method for determining soil organic matter and a proposed modification of the chronic acid titration method. Soil Science, 37, 29-38.

Yadav, A.N., Kumar, R., Kumar, S., Kumar, V., Sugitha, T., Singh, B., Chauhan, V., Dhaliwal, H.S., and Saxena, A.K. 2017. Beneficial microbiomes: biodiversity and potential biotechnological applications for sustainable agriculture and human health. Journal of Applied Biology and Biotechnology, 5, 45-57.

Yavasli, D.D. 2012. Recent approaches in aboveground biomass estimation methods. Aegean Geography Journal, 21(1), 39-49.

Received:10th August 2021
Accepted:19th February 2022