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ASSESSMENT OF SOIL AND FOREST BIOMASS CARBON STOCKS AT KADIGARH NATIONAL PARK OF BHALUKA IN MYMENSINGH DISTRICT, BANGLADESH

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The present study highlighted soil and forest biomass carbon stocks in *Shorea robusta* dominated national park of Bangladesh. Based on the Bangladesh Forest Inventory (Tree and Forest Resources of Bangladesh), soil organic carbon and forest biomass carbon stocks were estimated across five distinct zones (hill, Sal, coastal, Sundarban and village zones). However, these national-level inventories lack the granularity to inform management at the individual protected area, such as the national parks. An assessment was made to estimate soil and forest biomass carbon stocks at Kadigarh National Park (KNP) of Bhaluka Upazila in Mymensingh district, and the data was compared with other land uses and homestead forest adjacent to the national park. The total area of KNP is 344.14 ha. A total of 73 plots representing 20% of the total area of KNP were established for collecting soil samples and data on diameter at breast height (DBH) and height of forest tree species. The soil organic carbon stocks at 0–100 cm soil depth was found to be higher in agricultural field (90.00 ± 1.95 t ha^{-1}), followed by *Syzygium cumini* plantation, *Tectona grandis* plantation and *S. robusta* forest, and lower in *Acacia auriculiformis* plantation. The overall soil organic carbon stocks in KNP is 70.00 ± 1.58 t ha^{-1} and homestead forest is 62.00 ± 1.40 t ha^{-1}. The forest biomass in KNP was found to be 347 t ha^{-1}, but maximum biomass was attained in *S. cumini* plantation (526 t ha^{-1}) due to higher tree density among the other land uses. On the other hand, homestead forest (294 t ha^{-1}) attained minimum amount of forest biomass. The contribution of different carbon pools was also incorporated under the study. Thus, the overall carbon stocks in all carbon pools (above ground biomass, below ground biomass, leaf litter, herb & grass, downed woody debris and soil organic carbon) of KNP is 245.35 t ha^{-1}. Whereas, *S. cumini* plantation attained maximum carbon stocks (330.94 t ha^{-1}), followed by *A. auriculiformis* plantation (250.80 t ha^{-1}), *S. robusta* forest (232.20 t ha^{-1}), *T. grandis* plantation (225.39 t ha^{-1}) and homestead forest (205.40 t ha^{-1}). Accordingly, the O_2 released (460.80 t ha^{-1}) and CO_2 mitigation (900.40 t ha^{-1}) was estimated in KNP. The *S. cumini* plantation attained maximum amount of O_2 released (683.90 t ha^{-1}) and CO_2 mitigation (1214.50 t ha^{-1}), whereas the homestead forest attained minimum amount of O_2 released (383.10 t ha^{-1}) and CO_2 mitigation (753.80 t ha^{-1}). The total carbon stocks, O_2 released and CO_2 mitigation potential of KNP is 84431, 158566 and 309861 t ha^{-1}, respectively according to the areas in KNP. The findings of this research would be useful to develop a legacy of sustainable forest and land resources management policies to protect natural resources for future generations.

Keywords: allometric equations, bulk density, carbon stocks, forest biomass, Kadigarh National Park, soil organic carbon

INTRODUCTION

The soil is a major source of global carbon cycle. Soil organic carbon (SOC) stocks are the biggest ecosystem carbon repositories in the world. The global soil carbon pool of 2500 gigatons (Gt) includes about 1550 Gt of SOC and 950 Gt of soil inorganic carbon (SIC) (Eswaran & Van den 1992, IPCC 2000, Pan et al. 2002). The SOC pool to 1 m soil depth ranges from 30 t ha^{-1} in arid climates to 800 t ha^{-1} in organic soils in cold regions, with a predominant range of 50–150 t ha^{-1}. Conversion of natural to agricultural ecosystems causes depletion in the SOC pool by as much as 60% in soils of temperate regions and 75% or more in cultivated soils of the tropics. The depletion is exacerbated when the output of carbon exceeds the input and when soil degradation is severe (Lal 2004).

Forests play a vital role in global carbon flux and acts as carbon sink by storing large quantities of carbon for a long period of time. More than 40% of the global primary production in forest ecosystem is accomplished by tropical and sub-tropical forests. Tropical and sub-tropical forests are potentially capable to mitigate climate change and global warming by sequestering carbon from atmosphere (Beer et al. 2010). Land use change, particularly conversion of forest land to agricultural ecosystems depletes the soil carbon stock. Consequently, afforestation and management of forest plantations can enhance SOC stock through carbon sequestration (Wu & Cai 2012). Increasing the production of forest biomass may not necessarily increase the SOC stocks (Salunkhe et al. 2018). The rate of SOC sequestration, and the magnitude and quality of soil carbon stock depend on the complex interaction between climate, soil, tree species and management, and chemical composition of the litter, as determined by the dominant tree species. Soils in equilibrium with a natural forest ecosystem have high carbon density (Lal 2005).

The forests of Bangladesh are categorised into three major categories, namely evergreen to semi-evergreen hill forests, littoral mangrove forests, and deciduous Sal forests based on vegetation and ecology. The highly diverse hill forests are situated mainly in the Chittagong and Sylhet divisions (Khan et al. 2007). The Sundarban mangrove forest is the world's largest contiguous mangrove forest and is situated in the Bagerhat, Khulna and Satkhira districts. *Heritiera fomes* is the predominant species in this forest. The newly accreted islands of coastal Bangladesh underwent mangrove plantations and are dominated mainly by *Sonneratia apetala*. The deciduous Sal forests are located on relatively plain lands in the central districts of Bangladesh and are dominated by *Shorea robusta*. Although managed by smallholders and rural landowners, the homestead forests represent one of the most productive systems in Bangladesh (Kabir & Webb 2008).

Based on the Bangladesh Forest Inventory (Tree and Forest Resources of Bangladesh), soil organic carbon and forest biomass carbon stocks were estimated across five distinct zones (hill, Sal, coastal, Sundarban and village) (GoB 2020). Although the zone-wise forest inventory data was presented in this report, these national-level inventories lack the granularity to provide detailed inventories for individual protected areas such as the national parks. Therefore, the present study was undertaken to estimate the total carbon stocks (both soil and forests) in Kadigarh National Park (KNP) and compare it to other land uses adjacent to the national park.

MATERIALS & METHODS

Brief description of the study area

Kadigarh National Park (KNP) lies between latitudes 24° 19' 21" N and 24° 21' 06" N, and longitudes 90° 18' 45" E and 90° 20' 19" E (Figure 1). It is located at Bhaluka Upazila of Mymensingh district and is about 50 km northwest of the capital city Dhaka in Bangladesh. It is a natural *S. robusta* forest of Kadigarh Beat in Bhaluka Range under the control of Mymensingh Forest Division. The total area of this forest is 344.19 ha (850 acres). *Shorea robusta* is the dominant tree species of this park. The other associated tree species in this area are *Acacia auriculimormis*, *Acacia mangium*, *Tectona grandis*, *Terminalia chebula*, *Terminalia bellerica*, *Terminalia arjuna*, *Aquilaria malaccensis*, *Lagerstroemia speciosa*, *Swietenia macrophylla*, *Ficus benghalensis*, *Phyllanthus emblica*, *Borassus flabellifer*, *Syzygium cumini*, Gadila, *Zanthoxylum rhetsa*, *Aphananmixis polystachya*, *Fimbristylis miliacea*, *Neolamarckia cadamba*, *Senna siamea*, *Litsae glutinosa*, bamboos and rattan. Among others, animals such as fishing cats, civets, foxes, pythons, and monkeys are found in this forest. The national park is known for its rich biodiversity, hosting a variety of birds, snakes, and insect species. The forest area was gazetted as Kadigarh National Park by the Ministry of Environment, Forest and Climate Change in 2010 (Banglapedia 2010).

Plot layout

Soil sample collection and forest tree data measurement was carried out in circular plots by random sampling method. A total of 73 plots representing 20% of the total area of KNP were established for collecting soil samples and data on diameter at breast height (DBH) and height of forest tree species. In a circular plot, the radius of each plot is dependent on the density of the forest. Trees having >30 cm DBH were measured within the 19 m radius of the large plot (L plot). While trees with DBH of more than 10 cm to 30 cm were measured within the 8 m radius of the medium plot (M plot). Seedling and sapling data were collected within a radius of 2.5 m from the small plot (S plot). Leaf litter, herb and grass (LHG) and soil samples were collected at an 8-meter distance from the plot center at a 270° (West) bearing. Down woody debris data

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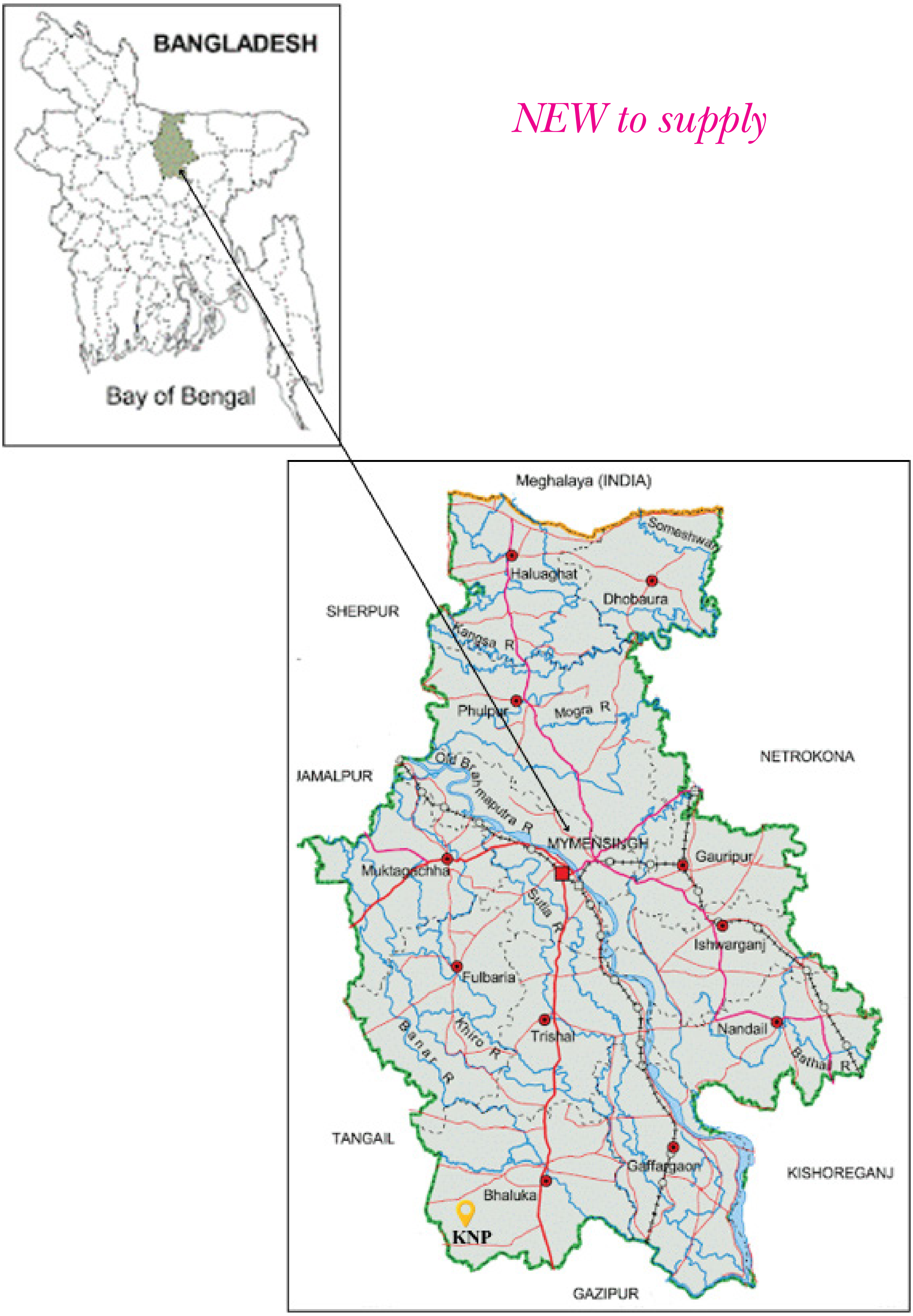

Figure 1 Location map showing the research area of the study

were collected along two transects within the medium plot (Figure 2). At the time of data and information collection, different factors such as land feature, crown cover, land management and disturbance were considered (GoB 2020).

Soil sample collection and analysis

The soil profiles up to 0–100 cm depth were excavated from the study area. The soil samples from five soil depths (0–20, 20–40, 40–60, 60–80 and 50–100 cm) were collected from the soil profiles of each plot using a cylindrical metal core sampler inserted into the soil to the desired depth and carefully removed to collect a known volume of soil sample. Samples from different soil depths were packed in plastic bags, labeled, and taken to the Soil Science Division laboratory at Bangladesh Forest Research Institute (BFRI), Chattogram for determination of bulk density (BD), moisture content (MC) and soil texture. Separately, composite soil samples were collected by a soil auger for analysis of soil pH, organic carbon, and total nitrogen. Soil samples were dried at 105 °C for 48 h and weighed. The bulk density was determined by core method (Blake & Hartge 1986), moisture content by gravimetric method (Blake 1965) and soil texture by hydrometer method (Bouyoucos 1962, Day 1965). The textural classes were determined using Marshall's Texture Triangle as defined by Soil Survey Division Staff (1993)

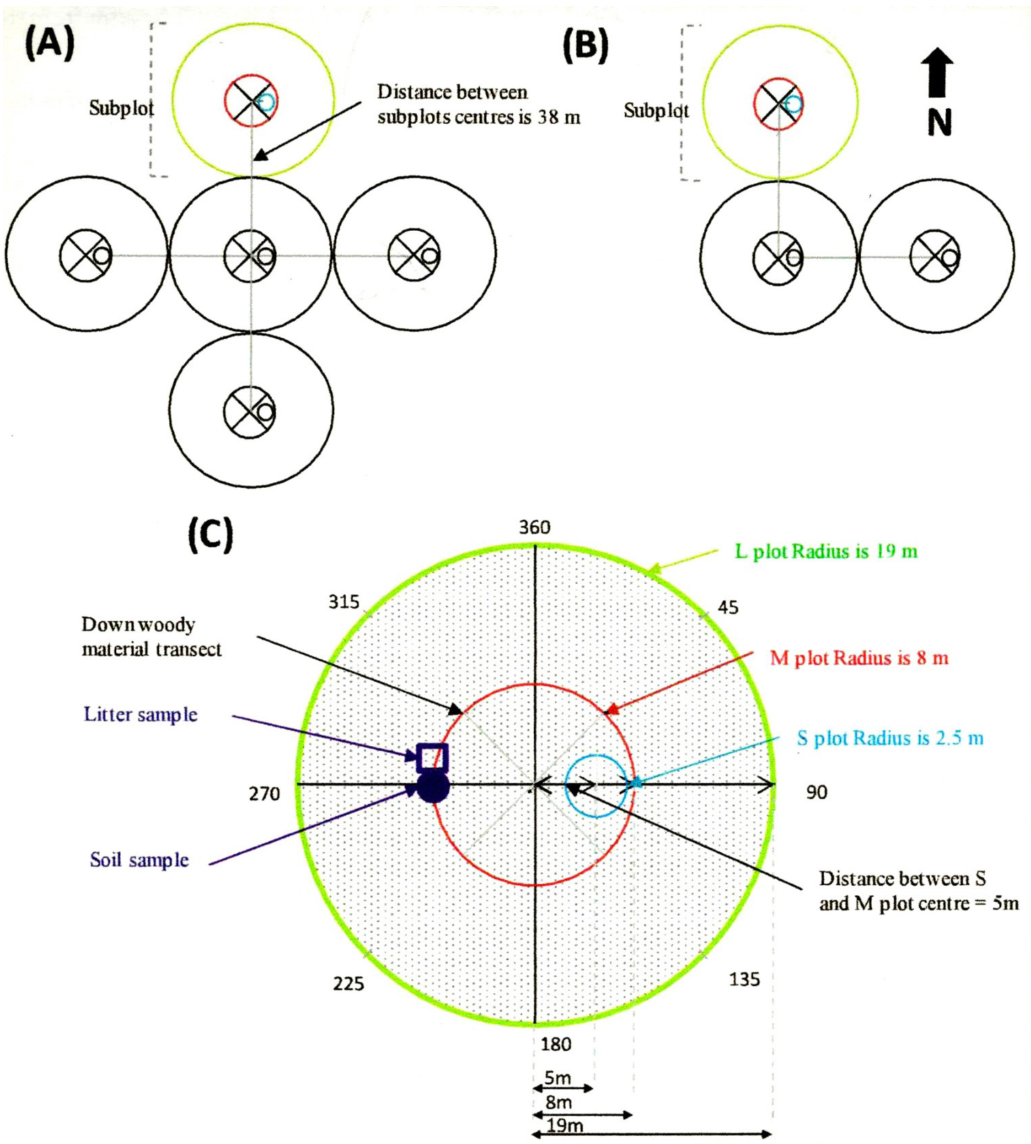

Figure 2 Sampling design of circular plot for soil sample and plant data collection

and named USDA soil classification. Soil pH was determined by a glass electrode pH meter (TOA-DK, Japan) by maintaining the ratio of soil to water at 1:2.5 and shaking for approximately 30 min (Jackson 1958). Organic carbon content of soil was determined by wet oxidation method (Walkley & Black 1934). For the determination of soil total nitrogen, the samples were digested by Kjeldahl's method as described by Jackson (1958). Total soil organic carbon (SOC) stocks were calculated by using the following formula described by Pearson et al. (2007):

$$\text{SOC stocks (t ha}^{-1}) = \text{SOC (\%)} \times \text{BD (g cm}^{-3}) \times \text{Soil depth (cm)}$$

Plant data collection

Tree growth parameters like DBH and height of the different forest tree species were recorded in each plot using diameter tape and Suunto-clinometer, respectively. The exact locations of sampling points were recorded by using a Global Positioning System (GPS, GARMIN *etrex-30x*).

Estimation of forest biomass and carbon

Forest biomass was estimated following the definition of above-ground biomass and below-ground biomass proposed by FAO (2018a, 2018b) for the Global Forest Resources Assessment 2020. All live trees and saplings were used for estimating above- and below-ground biomass.

Above-ground biomass and carbon of forest

The above-ground biomass (AGB) is the function of tree diameter, height, and wood density. The AGB contains biomass of trees, saplings, bamboo, and live stumps. The estimation procedure of AGB for trees and saplings, bamboo, and stumps are different (Hossain et al. 2019). In this regard, the following different allometric models or equations were used for estimating forest AGB (GoB 2020, Hossain et al. 2019, Hossain et al. 2020, Chameli et al. 2021):

$$\ln Y_{TSagb} = -2.46 + 2.17 \times \ln(D) + 0.367 \times \ln(H) + 0.161 \times \ln(\rho) \text{ for Sal zones} \quad \text{(i)}$$

$$\ln Y_{agb} = -6.0325 + 1.9715 \times \ln(D) + 0.8193 \times \ln(\rho) \text{ for village zone} \quad \text{(ii)}$$

$$\ln Y_{TSagb} = -2.459 + 1.869 \times \ln(D) + 0.800 \times \ln(H) \text{ for } \textit{Acacia auriculiformis} \quad \text{(iii)}$$

$$\ln Y_{TSagb} = -2.302 + 0.894 \times \ln(D^2 \times H) \text{ for } \textit{Swietenia macrophylla} \quad \text{(iv)}$$

$$\ln Y_{TSagb} = -3.005 + 0.923 \times \ln(D^2 \times H) \text{ for } \textit{Acacia mangium} \quad \text{(v)}$$

$$\ln Y_{TSagb} = -2.597 + 1.835 \times \ln(D) + 0.951 \times \ln(H) \text{ for } \textit{Senna siamea} \quad \text{(vi)}$$

$$\ln Y_{TSagb} = -2.180 + 0.875 \times \ln(D^2 \times H \text{ for } \textit{Tectona grandis} \quad \text{(vii)}$$

$$\ln Y_{TSagb} = -3.3592 + 2.1830 \times \ln(D) + 0.6787 \times \ln(H) \text{ for } \textit{Shorea robusta} \quad \text{(viii)}$$

$$\ln Y_{TSagb} = -0.8971 + 1.9908 \times \ln(D) \text{ for } \textit{Artocarpus heterophyllus} \quad \text{(ix)}$$

$$\ln Y_{TSagb} = -0.2272865 + 1.8017 \times \ln(D) \text{ for } \textit{Mangifera indica} \quad \text{(x)}$$

where Y_{TSagb} = tree or sapling above-ground biomass (kg), D = diameter at breast height of tree or sapling (cm), H = height of tree or sapling (m), – = wood density (kg m^{-3}) and ln = natural log.

Carbon in above-ground biomass (CAGB) is the sum of carbon from above-ground biomass of trees and saplings. The proportion of carbon in the above-ground biomass of trees and saplings is different. Thus, the computation methods are also different. The CAGB of trees and saplings were estimated using the allometric equations mentioned below which were developed under the BFI program and selected based on the different zones and tree species (GoB 2020, Hossain et al. 2019).

$$\ln(CAGB_{TS}) = -3.014 + 2.206 \times \ln(D) + 0.302 \times \ln(H) + 0.262 \times \ln(\rho) \text{ for Sal zones} \quad \text{(xi)}$$

$$\log_{10}(\sqrt{CAGB_{TS}}) = -0.630 + 0.614 \times \log_{10}(D^2) \text{ for } \textit{A. auriculimormis} \quad \text{(xii)}$$

$$\log_{10}(\sqrt{CAGB_{TS}}) = -0.652 + 0.607 \times \log_{10}(D^2) \text{ for } \textit{A. mangium} \quad \text{(xiii)}$$

$$\ln(CAGB_{TS}) = -3.9802 + 2.1660 \times \ln(D) + 0.6984 \times \ln(H) \text{ for } \textit{S. robusta} \quad \text{(xiv)}$$

where $CAGB_{TS}$ = carbon in above-ground biomass of tree or sapling (kg).

Below-ground biomass and carbon of forest

The below-ground biomass (BGB) consists of the live roots of trees and saplings. The estimation procedure of BGB for all trees and saplings in the study area is the same. The following allometric equation was used for estimating BGB (Pearson et al. 2007).

$$Y_{TSbgb} = \exp\left[-1.0587 + 0.8836 \times \ln\left(Y_{TSagb}\right)\right] \quad \text{(xv)}$$

where Y_{TSbgb} = tree or sapling below-ground biomass (kg).

Carbon in below-ground biomass (CBGB) is the sum of carbon in the BGB of trees and saplings. The CBGB of trees and saplings was estimated as 50% of the BGB (Hairiah et al. 2001, Matthews 1997).

$$CBGB_{TS} = BGB_{TS} \times 0.50 \quad \text{(xvi)}$$

where $CBGB_{TS}$ = carbon in below ground biomass of tree or sapling (kg).

Biomass and carbon of leaf litter, herb and grass

To determine the biomass of leaf litter, herb and grass (LHG), samples were taken destructively in the field within a small area of 1 m radius circular plot. Fresh samples were weighed in the field and the sub-sample was used to determine an oven-dry-to-wet mass ratio, which was used to convert the total wet mass to oven-dry mass. A sub-sample was taken to the laboratory and oven dried until constant weight to determine water content. For the forest floor (herbs, grass, and litter), the amount of biomass per unit area was given by:

$$LHG = \frac{W_{field}}{A} \times \frac{W_{subsample,\ dry}}{W_{subsample,\ wet}} \times 10{,}000 \quad \text{(xvii)}$$

where LHG = biomass of leaf litter, herbs, and grass (t ha^{-1}), W_{field} = weight of the fresh field sample of leaf litter, herbs, and grass destructively sampled within an area of size A (g); A = size of the area in which leaf litter, herbs, and grass were collected (ha), $W_{subsample,\ dry}$ = weight of the oven dry sub-sample of litter, herbs, and grass (g); and $W_{subsample,\ wet}$ = weight of the fresh sub-sample of litter, herbs, and grass (g) (ICIMOD 2010).

The carbon content in leaf litter, herb and grass (CLHG) was calculated by multiplying the biomass of leaf litter, herb and grass with the IPCC (2006) default carbon fraction of 0.47.

$$CLHG = BLHG \times 0.47 \quad \text{(xviii)}$$

where CLHG = carbon in leaf litter, herb and grass (kg), and BLHG = biomass of leaf litter, herb and grass (kg).

The biomass and carbon of downed woody debris was also computed under the study. Finally, the total carbon stocks density was calculated by summing the carbon stock densities of the individual carbon pools of that forest type using the following formula (ICIMOD 2010).
Carbon stock density of the study area:

$$C_{FT} = CAGB_{TS} + CBGB_{TS} + CLHG + CDWD + SOC \quad \text{(xix)}$$

where C_{FT} = carbon stock density of the study area (t ha^{-1}), $CAGB_{TS}$ = carbon in above-ground biomass of trees and saplings (t ha^{-1}), $CBGB_{TS}$ = carbon in below-ground biomass of trees and saplings (t ha^{-1}), CLHG = carbon in leaf litter, herb and grass (t ha^{-1}), CDWD = carbon in downed woody debris (t ha^{-1}) and SOC = soil organic carbon stocks (t ha^{-1}).

Data analysis

The collected and analytical data from field and laboratory were analysed using descriptive statistics such as means, standard deviation, standard error, minimum and maximum values to summarise the data. One-way analysis of variance (ANOVA) was performed to identify whether there were any significant differences in the mean values of the soil properties among the different plots and soil depths. When the F-test was significant at 5% level of significance, Tukey's post-hoc test was employed to test differences among means. The statistical analysis was performed using MINITAB software (version 17) and SPSS-22 software. Microsoft Excel 19 was used to produce bar charts.

RESULTS

Determination of bulk density and soil organic carbon

The soil texture of Kadigarh National Park (KNP) is sandy loam to sandy clay loam. The soil bulk density (g cm^{-3}) of KNP was found decreasing from surface to sub-stratum of the soil profiles. Similar trend was observed in all land uses except homestead. The soil bulk density of homestead site was found increasing from surface to sub-stratum of the soil profiles. *Acacia auriculiformis* plantation (1.51–1.39) and agricultural field (1.49–1.45) attained higher and homestead (1.47–1.34) attained lower soil bulk density, in all soil depths compared to other land uses and KNP (Table 1). On the other hand, soil organic carbon was found higher in the surface soil (0–20 cm) of agricultural field (1.31%), followed by *S. cumini* plantation (0.90%) and KNP (0.87%), and lower in *A. auriculiformis* plantation (0.69%), indicating highly significant difference at 1% level ($p<0.01$). On the other hand, 5% level ($p<0.05$) of significant differences were observed in 40–60 cm soil depth for soil organic carbon content (Table 1).

Determination of soil physical and chemical properties

Agricultural field attained maximum soil pH (5.50), moisture (26.13%) and nitrogen (0.19%) content compared to KNP and other land uses in the surface soil (0–20 cm), showing highly significant differences at 1% and 5% level in soil pH and moisture content, respectively. Significant differences were observed among all land uses including KNP for potassium content but not for phosphorous, sulfur, calcium, and magnesium (Table 2).

Estimation of soil organic carbon stocks

The soil organic carbon stocks up to 0–100 cm soil depth was found higher in agricultural field (90.00 ± 1.95 t ha^{-1}) followed by *S. cumini* and *T. grandis* plantations and *S. robusta* forest, and lower in *A. auriculiformis* plantation. The overall soil organic carbon stocks in KNP was found 70.00 ± 1.58 t ha^{-1} and homestead forest was 62.00 ± 1.40 t ha^{-1} (Figure 3).

Measurement of DBH and height of important tree species

Growth parameters such as diameter at breast height (DBH) and height of tree species were recorded in this study. The maximum DBH was found in *A. auriculiformis* × *A. mangium* and *B. flaballifer* followed by *T. grandis*, *S. robusta*, *S. cumini*, *A. auriculiformis*, *Z. rhesta*, *Lannea coromandelica*, *Mangifera indica* and minimum in *Areca catechu* and *Moringa oleifera* tree species.

Table 1 Soil bulk density and organic carbon in Kadigarh National Park (KNP) and different land uses

Forest type	Bulk density (g cm^{-3})					Organic carbon (%)				
	0–20 cm	20–40 cm	40–60 cm	60–80 cm	80–100 cm	0–20 cm	20–40 cm	40–60 cm	60–80 cm	80–100 cm
KNP	1.45a (±0.07)	1.41a (±0.06)	1.39a (±0.06)	1.40ab (±0.05)	1.40a (±0.12)	0.87b (±0.21)	0.51a (±0.11)	0.40ab (±0.07)	0.37a (±0.07)	0.31a (±0.06)
S. robusta forest	1.46a (±0.07)	1.40a (±0.07)	1.38a (±0.06)	1.40ab (±0.04)	1.36a (±0.16)	0.74b (±0.06)	0.45a (±0.15)	0.41ab (±0.06)	0.34a (±0.05)	0.30a (±0.11)
A. auriculiformis plantation	1.51a (±0.01)	1.46a (±0.04)	1.40a (±0.03)	1.39ab (±0.02)	1.46a (±0.03)	0.69b (±0.03)	0.42a (±0.00)	0.31b (±0.04)	0.34a (±0.02)	0.30a (±0.02)
T. grandis plantation	1.44a (±0.11)	1.38a (±0.05)	1.41a (±0.02)	1.41ab (±0.01)	1.43a (±0.09)	0.81b (±0.04)	0.55a (±0.05)	0.49a (±0.06)	0.42a (±0.06)	0.32a (±0.02)
S. cumini plantation	1.47a (±0.09)	1.46a (±0.02)	1.46a (±0.04)	1.34b (±0.04)	1.37a (±0.01)	0.90ab (±0.06)	0.54a (±0.06)	0.40ab (±0.01)	0.46a (±0.10)	0.34a (±0.05)
Homestead forest	1.35a (±0.04)	1.35a (±0.03)	1.34a (±0.02)	1.42ab (±0.04)	1.47a (±0.05)	0.84b (±0.02)	0.86a (±0.04)	0.35ab (±0.04)	0.32a (±0.02)	0.28a (±0.04)
Agriculture field	1.49a (±0.04)	1.47a (±0.01)	1.47a (±0.06)	1.47a (±0.04)	1.45a (±0.04)	1.31a (±0.0)	0.65a (±0.02)	0.42ab (±0.03)	0.36a (±0.02)	0.31a (±0.04)
F-test	ns	ns	ns	*	ns	**	ns	*	ns	ns

*5% level of significance; **1% level of significance; ns = not significant; values in parentheses are ± standard deviation (SD)

Table 2 Soil physical and chemical properties of Kadigarh National Park (KNP) and different land uses

Forest type	pH	MC	N	P	S	K	Ca	Mg
		(%)		(ppm)			(meq 100g^{-1})	
KNP	4.66c (±0.44)	22.72ab (±2.32)	0.12a (±0.04)	5.50a (±4.31)	9.67a (±5.55)	0.16ab (±0.06)	1.76a (±1.04)	1.0a (±0.45)
S. robusta forest	4.32c (±0.08)	23.05ab (±0.97)	0.11a (±0.06)	3.67a (±1.15)	4.67a (±4.73)	0.22ab (±0.01)	9.98a (±0.84)	0.68a (±0.01)
A. auriculiformis plantation	4.65bc (±0.04)	18.47c (±0.53)	0.11a (±0.04)	10.1a (±1.39)	9.67a (±2.08)	0.11b (±0.03)	1.66a (±1.0)	0.96a (±0.19)
T. grandis plantation	4.54bc (±0.07)	21.10bc (±1.21)	0.11a (±0.01)	4.67a (±2.08)	14.0a (±4.0)	0.13ab (±0.01)	2.54a (±0.99)	1.67a (±0.85)
S. cumini plantation	5.34ab (±0.15)	24.35ab (±0.53)	0.12a (±0.01)	3.67a (±0.58)	16.33a (±3.06)	0.25a (±0.03)	2.12a (±0.47)	1.04a (±0.21)
Homestead forest	4.58bc (±0.03)	22.21abc (±0.56)	0.12a (±0.01)	5.0a (±1.0)	4.0a (±3.61)	0.18ab (±0.01)	1.99a (±1.23)	0.88a (±0.06)
Agriculture field	5.50a (±0.05)	26.13a (±1.31)	0.19a (±0.01)	6.0a (±1.0)	9.33a (±4.04)	0.10b (±0.04)	1.25a (±1.46)	0.75a (±0.08)
F-test	**	**	ns	ns	ns	*	ns	ns

*5% level of significance; **1% level of significance; ns = not significant; values in parentheses are ± standard deviation (SD)

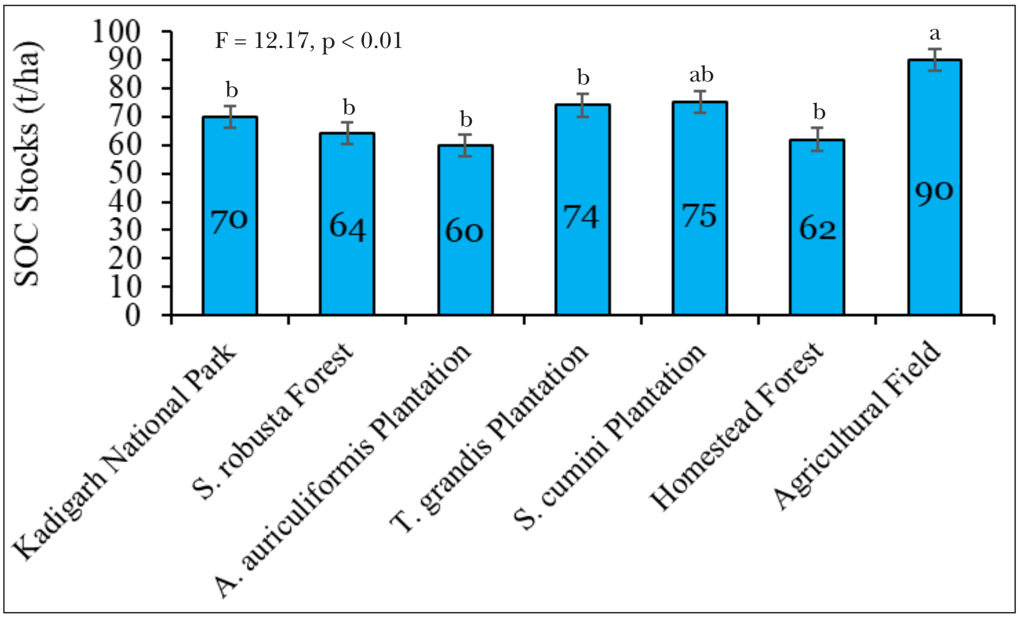

Figure 3 Soil organic carbon (SOC) stocks (t ha^{-1}) of Kadigarh National park and other land uses. Bars with different letters are significantly different ($p < 0.01$, one-way ANOVA)

The height of tree species was also found maximum in *A. auriculiformis* × *A. mangium*, followed by *S. robusta*, *T. grandis*, *A. auriculiformis*, *S. cumini* and *B. flabellifer*, and minimum in *Artocarpus heterophyllus* and *Moringa oleifera*. Significant differences at 1% level was observed among the tree species in both DBH and height (Figure 4).

Estimation of forest biomass and carbon stocks

The forest biomass in KNP is 347 t ha^{-1}, but maximum biomass was attained in *S. cumini* plantation (526 t ha^{-1}) due to higher tree density compared to the other land uses. The biomass of *A. auriculiformis* plantation attained 451 t ha^{-1},

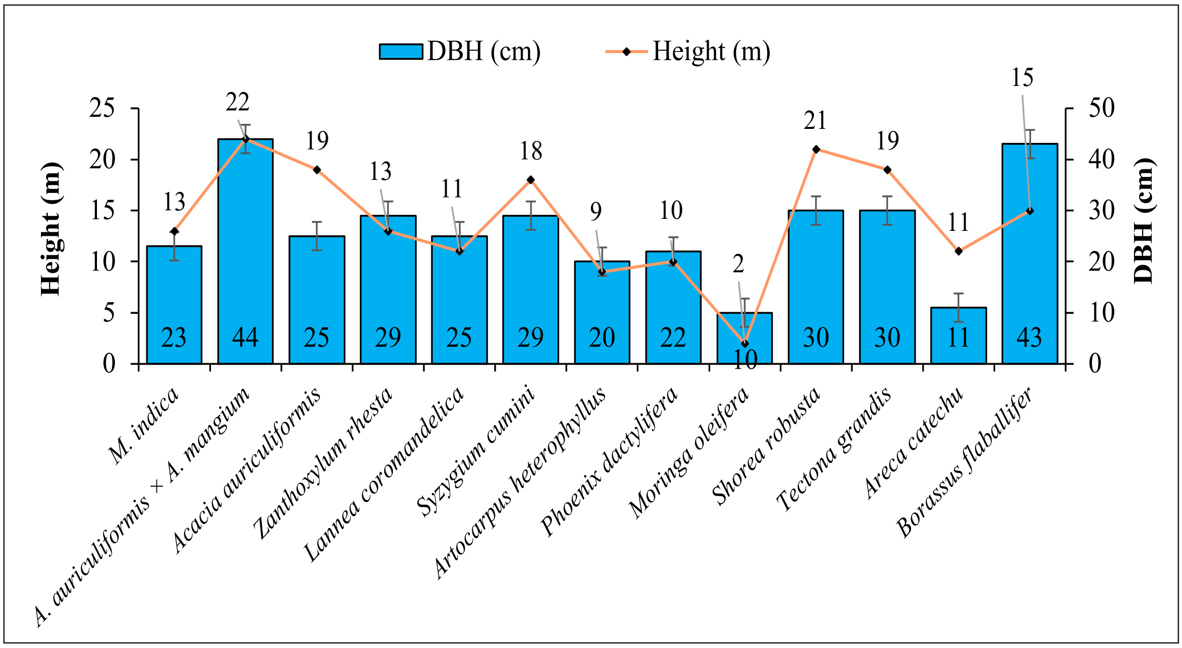

Figure 4 Diameter at Breast Height (DBH) and height of important tree species collected from Kadigarh National Park

whereas *S. robusta* forest and *T. grandis* plantation attained similar amount of forest biomass content. On the other hand, homestead forest attained minimum amount of forest biomass (Figure 5). As a result, the forest biomass carbon was found maximum in *S. cumini* plantation (256 t ha^{-1}), followed by *A. auriculiformis* plantation (191 t ha^{-1}), KNP (173 t ha^{-1}), *S. robusta* forest (160 t ha^{-1}) and *T. grandis* plantation (152 t ha^{-1}), and minimum in homestead (143 t ha^{-1}) forest (Figure 6).

Therefore, the overall carbon stocks in all carbon pools (above ground biomass; below ground biomass; leaf litter, herb & grass, downed woody debris and soil organic carbon) of KNP was found 245.35 t ha^{-1}, whereas *S. cumini* plantation

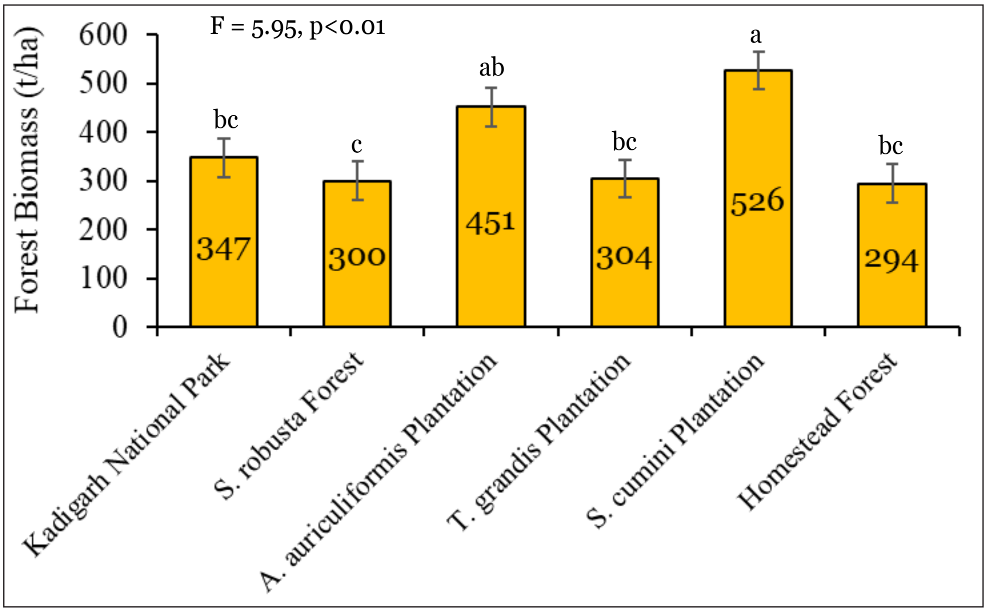

Figure 5 Forest biomass (t ha^{-1}) of Kadigarh National Park and other land uses. Bars with different letters are significantly different (p < 0.01, one-way ANOVA)

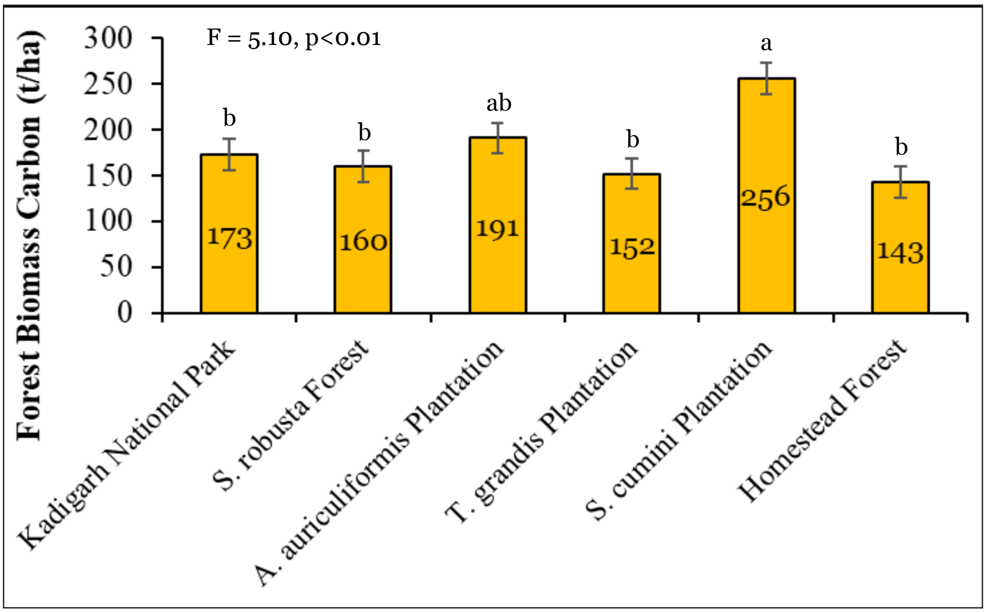

Figure 6 Forest biomass carbon (t ha^{-1}) of Kadigarh National Park and other land uses. Bars with different letters are significantly different ($p < 0.01$, one-way ANOVA)

attained maximum carbon stocks (330.94 t ha^{-1}) followed by *A. auriculiformis* plantation (250.80 t ha^{-1}), *S. robusta* forest (232.20 t ha^{-1}), *T. grandis* plantation (225.39 t ha^{-1}) and homestead forest (205.40 t ha^{-1}). The oxygen (O_2) released and carbon dioxide (CO_2) mitigation potentials of the study area were measured by using total forest biomass carbon and total forest carbon stocks by multiplication with the factors of 2.67 and 3.67 (C equivalent of O_2 and CO_2), respectively. Accordingly, the O_2 released (460.80 t ha^{-1}) and CO_2 mitigation (900.40 t ha^{-1}) was estimated in KNP and other land uses. The *S. cumini* plantation attained maximum amount of the O_2 released (683.90 t ha^{-1}) and CO_2 mitigation (1214.50 t ha^{-1}), whereas homestead forest attained minimum amount of the O_2 released (383.10 t ha^{-1}) and CO_2 mitigation (753.80 t ha^{-1}). Due to the higher density of tree species, *S. cumini* plantation showed higher amount of carbon stocks as well as O_2 released and CO_2 mitigation potentials. Hence, the total carbon stocks, the O_2 released and the CO_2 mitigation potential of KNP was 84431, 158566 and 309861 t ha^{-1}, respectively (Table 3).

Table 3 Carbon stocks, O_2 released and CO_2 mitigation potential of different land uses at Kadigarh National Park

Forest type	Carbon stock (t ha^{-1})	Oxygen release (t ha^{-1})	Carbon dioxide mitigation (t ha^{-1})
Kadigarh National Park	245.3^{b}	460.8^{b}	900.4^{b}
S. robusta forest	232.2^{b}	461.1^{b}	852.1^{b}
A. auriculiformis plantation	250.8^{ab}	509.5^{ab}	920.4^{ab}
T. grandis plantation	225.3^{b}	405.5^{b}	827.2^{b}
S. cumini plantation	330.9^{a}	683.9^{a}	1214.5^{a}
Homestead forest	205.4^{b}	383.1^{b}	753.8^{b}
F-test	**	**	**
Total (ton) in KNP	84431	158566	309861

Values in the same column having different small letters in superscripts are significantly different ($p < 0.01$)

Contribution of different carbon pools in total carbon stocks

The carbon stocks measurement of different carbon pools varied from different ecosystems and land uses due to vegetation types, species composition, and site conditions as well as climatic edaphic factors. The study result revealed that carbon in above-ground biomass (CAGB) in all land uses including national park was found almost similar (55.37–60.53%) of total carbon stocks under the study. The percentage of SOC stocks was found higher in *T. grandis* plantation (32.62%) followed by homestead forest (30.15%) and KNP (28.65%), but lower in *S. cumini* plantation (22.60%). On the other hand, carbon in below-ground biomass (CBGB) was found higher in *S. cumini* plantation (20.85%) and lower in *S. robusta* forest (9.34%). The percentage of carbon in leaf litter, herb, and grass (CLHG) and carbon in downed woody debris (CDWD) were found <1% in KNP and other land uses, except in *A. auriculiformis* plantation (1.30%) and homestead forest (1.12%) for CLHG (Figure 7).

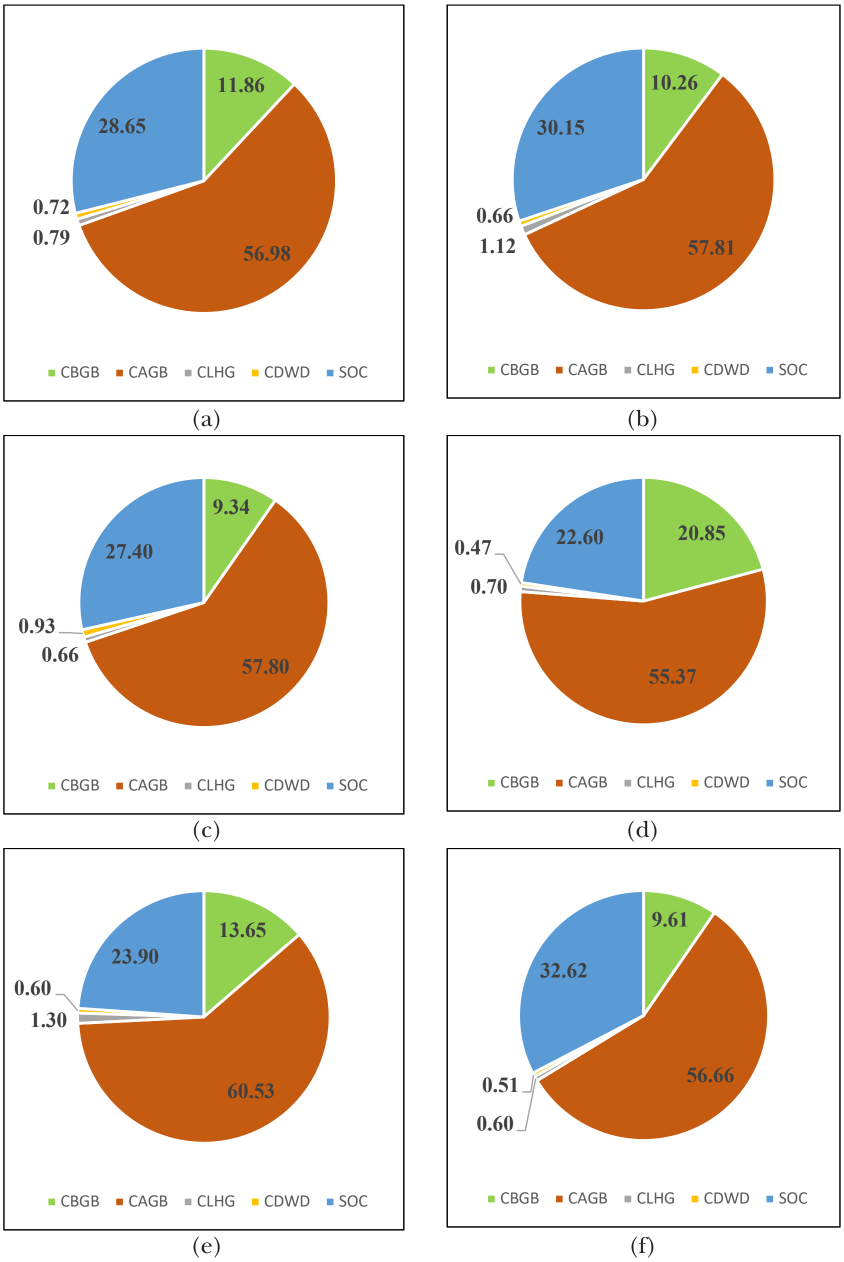

Figure 7 Contribution of different carbon pools in Kadigarh National Park and different land uses. (a) Kadigarh National Park; (b) Homestead forest; (c) *Shorea robusta* forest; (d) *Syzygium cumini* plantation; (e) *Acacia auriculiformis* plantation; (f) *Tectona grandis* plantation

DISCUSSION

The soil bulk density is an important physical property of soil. There was a gradual increase in bulk density with the increase in soil depth observed in the study area. The topsoil layer had lower bulk density indicating that the soil was better for plant growth compared to other soil depths which could be attributed to the higher SOC concentration in the top layer of soil. The bulk density was found to have decreased from top to bottom with the increase in soil depth in different ecological regions, as reported by Sharma & Kafle (2020) and Pandey & Bhusal (2016). The bulk density results obtained in the present study supported the findings from other investigators (Akhtaruzzaman 2016, Gupta et al. 2010, Lee et al. 2009). Han et al. (2010) reported of an increase in soil bulk density with soil depth in different soils of Loess Plateau, China. Loose soils have lower bulk density and compact soils have higher bulk density. Coarse textured or sandy soils tend to have a higher bulk density. Osman (2013) reported that forest soils are more porous in nature and possess lower bulk density than cultivated soils. Findings from Rahman (2024) revealed that soil bulk density was found to be higher in different *S. robusta* forest areas in the Cumilla, Tangail and Gazipur districts of Bangladesh. Singh et al. (2001) found higher bulk density values in both degraded and slightly degraded lands compared to undisturbed site. On the other hand, Gnanamoorthy et al. (2019) observed that higher bulk density reduces the volume of macropores leading to reduction in gaseous exchanges.

Soil organic carbon (SOC) is an important component of the global carbon cycle which involves the cycling of carbon through plants and soils. Litterfall in the forest floor is the major source of soil organic carbon and soil organic matter. The overall findings of the present study revealed that the surface soil (0–20 cm soil depth) contained a higher amount of soil organic carbon, which decreased with increasing soil depth in all land uses studied. Shaifullah et al. (2008) reported that generally, the soils of forest areas possessed high organic matter content at the surface. This is due to the contribution of the litterfall. Subsoil also receives organic matter from the occasional death and decay of tree roots. However, soil organic matter in forest soil decreases rapidly with depth. The results from the present study support the above statement. Similar findings were reported by Aktaruzzaman (2016) and Hossain & Sattar (2002). Another study by Akhtaruzzaman et al. (2015) recorded higher soil organic carbon in the planted forest soil compared to the adjacent barren soil and cultivated land soil. The phenomenon was ascribed to the addition of soil organic carbon from tree cover. Mia et al. (2016) also found a higher amount of soil organic carbon in a mixed forest stand in comparison to a pure forest stand. Biswas et al. (2012) reported that soil organic carbon varied from 0.54% in a slashed and burnt site to 1.55% in a forested site.

Soil acts as the largest carbon reservoirs in the terrestrial ecosystem and forest soils represent one of the major carbon sinks on Earth. Most studies are concerned only on the topsoil (0–30 cm), although carbon sequestration or loss may also occur in deeper soil layers (Bird et al. 2002, Fontaine et al. 2007). Iqbal & Tiwari (2017) reported higher SOC stocks at the top surface layer (0–20 cm), followed by the middle depth (20–50 cm) with a decreasing trend and the least SOC stocks were found at lower soil depth (50–100 cm), across all land uses. Pandey & Bhusal (2016) reported that the highest amount of SOC stocks was found in the uppermost soil horizon in the Hill and Terai forests. They also reported that the SOC stocks were found highest at 0–20 cm (28.45 and 36.60 t ha^{-1}) and lowest at 80–100 cm (16.90 and 9.40 t ha^{-1}) in the Hill and Terai forests, respectively. The main reason for the difference observed in the SOC density is because of the differences in SOC concentration and bulk density of soil. Generally, SOC concentration decreases and bulk density increases with increasing soil depth in all forest types. Baul et al. (2021) found that the topsoil carbon was 10–25% higher than the deeper soil depending on the altitude, due to the deposition of litterfall. Jeyanny et al. (2014) mentioned that soil carbon pools were comparable (100–120 Mg C ha^{-1}) with aboveground biomass pools at the summit and toeslope position of the montane forest. They also reported that carbon stocks were significantly higher in the tropical montane forest where litter and soil C stocks at the summit were three and five folds significantly higher, respectively compared with the lowland forest. The study of Shapkota & Kafle (2021) revealed that the SOC stocks in the upper soil layer (0–20 cm) were higher than in the lower soil horizon

(40–60 cm). This might be due to the variation in the time of soil formation. They also reported that the newly formed upper horizon could have contained more carbon. A similar result was reported by Mishra (2010) in SOC stocks of Chapako Community Forest, Kathmandu, and Ranjitkar (2010) in the temperate forest of Shivapuri Nagarjun National Park, Nepal. The result from this study is closely related to the above statement.

Forest biomass may be varied by different factors, such as tree species, climatic conditions, site conditions, forest types with its composition and management practices which ultimately influence the architecture of tree and biomass partitioning. The Bangladesh Forest Inventory (BFI) report on Tree and Forest Resources of Bangladesh (2020), indicated that the national average of total carbon density including all carbon pools across the different zones (hill, Sal, Sundarbans, coastal and village zones) was 248.97 t ha^{-1} (GoB 2020). This result is almost similar to the findings from the present study. Mukul et al. (2014) reported that the average carbon density in Bangladesh forest was 175.5 t ha^{-1} (considering SOC stocks up to 30 cm soil depth) which was closely related to the findings from this study. They also reported that carbon density in *S. robusta* forest was 202.2 t ha^{-1} (biomass 153.9 t ha^{-1} and soil 48.3 t ha^{-1}). Farukh et al. (2023) revealed that *Bombax ceiva* and *Limonia acidissima* received the maximum and minimum green, dry, and C values. They also found that *Monoon longifolium* (264,768 kg yr^{-1}), *Swietenia mahagoni* (257,290 kg yr^{-1}), *Acacia lebbeck* (118,310 kg yr^{-1}), *Mangifera indica* (78,906 kg yr^{-1}) and *T. grandis* (51,744 kg yr^{-1}) are the topmost five C stock accumulating trees whilst *A. lebbeck* is the major C stock accumulating tree within Bangladesh Agricultural University. The national level of biomass carbon in Forest Department (FD) managed forests in Bangladesh was estimated by many researchers. Based on satellite data, Saatchi et al. (2011) estimated the biomass carbon in FD-managed forests of Bangladesh as 70.5 t ha^{-1}. Whereas, based on forest inventory data, Brown (1997) and Gibbs & Brown (2007) reported the value to be 92 t ha^{-1} and 158 t ha^{-1}, respectively. DeFries et al. (2002), Gibbs et al. (2007) and IPCC (2006) reported that the biomass carbon estimation of Bangladesh forest was 137 t ha^{-1}, 93 t ha^{-1} and 65 t ha^{-1}, respectively by using harvest data. Abd-Majid et al. (2021) reported that carbon analysis of *Aquilaria* spp. in stem, branches and foliage revealed an average carbon content of 40.35% and average carbon density was 285 kg per tree and 9353 kg ha^{-1}. Their findings also provided baseline information on the biomass and carbon stock measurements for plantation-grown *A. malaccensis* and supported plantation in accumulating biomass and carbon storage. Banik et al. (2018) reported that the total biomass carbon density was higher in *S. robusta* plantation (216.68 t ha^{-1}) than natural *S. robusta* forest (167.64 t ha^{-1}), and this was closely related to the present study.

CONCLUSIONS

The present study highlighted soil and forest biomass carbon stocks of a *S. robusta* dominated national park in Bangladesh. This study found that Kadigarh National Park stores a total of 245.35 t C ha^{-1}, with *S. cumini* plantation being the most effective land use for carbon sequestration. There is no doubt that soil and forest play a key role in maintaining and conserving ecosystem biodiversity. The future of soil and forest carbon stocks will depend on climate change, land use and land cover, and feedbacks within and between these complex factors. Soil erosion is the most widespread form of soil degradation and has a great impact on the global carbon cycle, which partially is accountable for climate change and global warming. The present study suggested that change in land cover and land use generally leads to decrease in total carbon density of an area. Therefore, soil and forest carbon losses must be minimised through appropriate land use practices, and steps should be considered for addressing climate change and proposing climate mitigation strategies.

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