Article

Assessment of carbon stock and sequestration potential in sub-tropical forests of Darjeeling, eastern Himalaya

Darshana Tolangay, **Saurav Moktan**
Department of Botany, University of Calcutta, 35, B.C. Road, Kolkata, 700019, West Bengal, India
E-mail: smbot@caluniv.ac.in

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Abstract
The present study deals with the assessment of species composition, biomass, carbon stock and carbon sequestration potential of sub-tropical forests of Darjeeling, eastern Himalaya. Tree density, basal area, index and diameter class were used to assess the structural attributes of forest trees. The importance value score for the tree varied from 1.803 to 2.665. The Shannon diversity index, concentration of dominance, evenness index and Menhinick richness index were, 3.588, 0.032, 0.948 and 2.566, respectively. The assessment of biomass was based on diameter at breast height, tree height and wood density. Biomass was estimated using generalized allometric equation which was later converted to the carbon stock. The study site stored 33.53 Mg C ha^{-1} total carbon stock and 123.048 Mg CO_2 ha^{-1} carbon dioxide equivalent. *Schima wallichii* was the dominant species in terms of carbon storage. The correlation between aboveground biomass with height and diameter squared height (D^2H) showed significant positive correlation whereas, moderate correlation was observed with diameter. Nevertheless, the findings from this study will provide baseline information for carbon pool accounting and climate change mitigation in Himalayan forests.

Keywords sub-tropical; carbon; aboveground; belowground; biomass; sequestration.

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1 Introduction

A series of assessment reports from the Intergovernmental Panel on Climate Change provides unequivocal evidences that climate change is happening. The IPCC sixth assessment report outlines that continuous increase in the frequency of extreme events is of global concern and have the potential to impact both natural and human systems (IPCC, 2022). Human activities such as fossil fuels burning (Jarvis, 1989), tropical land-use changes and forestry activities (Bhadwal and Singh, 2002), chiefly deforestation and forest degradation (Mandal et al., 2013; Pascua et al., 2021) have contributed to substantial increase in the atmospheric concentrations of greenhouse gases (GHGs). Burning of fossil fuels is estimated to have emitted 6.3 Gt C $year^{-1}$ (Kumar et al., 2013) and tropical deforestation and forest degradation release 1.4 Gt C $year^{-1}$ (Houghton, 2012).The global CO_2 concentration has increased substantially from 227 ppm at the beginning of the industrial era to 409.85 ppm in 2019 (Dlugokencky and Tans, 2021). At the current rate of atmospheric GHGs rise, it is likely that the average temperature on the earth's surface will increase by 1.5°C of global warming over the decade (Zhang and Liu, 2012; IPCC, 2021).

The elevated level of GHGs, especially carbon dioxide in the atmosphere calls for urgency in adopting effective measures to mitigate climate change (Sharma et al., 2011; Zhang and Liu, 2012). Forests, as the largest carbon reservoir in terrestrial ecosystems, play an important role in mitigating elevated atmospheric CO_2 concentrations and preventing global warming (Dimri et al., 2014; Zhou et al., 2019; Ali et al., 2020). Aboveground biomass (AGB), belowground biomass (BGB), dead wood, litter and soil organic matter are the five major carbon pools in forest ecosystems (Rai et al., 2018). Forests cover 4.06 billion hectares globally, approximately 31% of the total land surface (FAO and UNEP, 2020). They account for 80% of the above ground and 40% of the belowground biomass carbon pools in terrestrial ecosystems (Dixon et al., 1994). Forest biomass is one of the fundamental parameters for assessing ecosystem productivity and determining their energy potential (FAO, 2008; Palchowdhuri et al., 2016; Kumar et al., 2019). Estimation of AGB is the most important aspect of studies of carbon stocks (Ketterings et al., 2001). Furthermore, study on biomass estimation of forest ecosystems is essential for determining any changes in forest structure and condition (Brown et al., 1999). The United Nations Framework Convention on Climate Change (UNFCCC) has greatly emphasized on the accurate estimation of carbon stocks at local and regional levels (Brown, 2002). As a developing country, India has taken initiatives such as Reducing Emissions from Deforestation and Forest Degradation (REDD) and REDD+ to increase forest biomass and carbon by limiting deforestation and forest degradation (Kumar and Mutanga, 2017). The global forest carbon stock including all carbon pools was estimated to be 662 Gt C, with 300 Gt C stored in soil organic matter, 295 Gt C in living biomass, and 68 Gt C in dead wood and litter (GFGR, 2021). India's carbon stock is estimated to be 7,204 million tonnes (FSI, 2021). The carbon pool of a forest ecosystem varies with the age structure (Clark et al., 2004), forest type (Wei et al., 2013) and dominant tree species (Gogoi et al., 2020). The change in the climatic behaviour over the years, results in the changes in structure, composition and function of forest ecosystems (Chakraborty et al., 2018).

Tropical forests spread over 1949 million hectares world-wide and accounts for approximately 50% of forest biomes (Pan et al., 2011). The tropical forest ecosystem has been playing a crucial role in mitigating the atmospheric concentration of carbon dioxide and associated climate change impacts. Dixon et al. (1994) and Clark et al. (2001) reported nearly 40% of terrestrial carbon is contributed by these forests. Tropical forests store large quantities of carbon ca. 247 Gt C in vegetation (Saatchi et al., 2011) and 383 Gt C in soil (Raha et al., 2022). In India, these forests constitute nearly 86% of forested area, out of which 53% is dry deciduous, 37% moist deciduous and the remaining is wet evergreen or semi evergreen (Singh and Singh, 1991). The tropical and subtropical forests are among the most productive ecosystems accounting more than one-third of global gross primary productivity (Salunkhe et al., 2014). Because of higher net productivity, these forests are more effective in estimating carbon stocks than any other forests (Brown et al. 1989; Gogoi et al., 2017).

Tree biomass can be achieved by destructive, non-destructive and through remote sensing and geographical information system (GIS) methods (Lu, 2006; Vashum and Jayakumar, 2012). The destructive method is the direct method and the most accurate approach for estimation of forest carbon stock (Gibbs et al., 2007). However, cutting or harvesting of trees and weighing the different components is expensive, destructive and time consuming (Lodhiyal and Lodhiyal, 2003; Ravindranath and Ostwald, 2008) and not applicable in certain areas containing threatened species (Gibbs et al., 2007). The non-destructive method is the most reliable approach for estimating forest carbon stock by developing allometric relationships between biomass of a tree and readily measured biometric parameters such as diameter at breast height (DBH), tree height and wood density (Salunkhe et al., 2018). Available generalized models are useful tools for estimating biomass of forest non-destructively (Brown et al., 1989; Chave et al., 2001). In the present study, allometric equation has been used for estimating biomass, where measurable tree parameters such as DBH and tree height were considered. In spite of rich and diverse forests, most of the studies on carbon stock biomass estimation have been carried out focusing tropical forests (Salunkhe et al., 2014; Salunkhe et al., 2016; Behera et al., 2017; Joshi and Dhyani, 2019; Yadav et al., 2022; Thakrey et al., 2022), tropical evergreen forests (Mani and Parthasarathy, 2007), tropical semi evergreen forests (Baishya et al., 2009), tropical wet evergreen forests (Gogoi et al., 2017). Only sporadic studies are available regarding subtropical forests ecosystem (Gogoi et al., 2019; Dhangwal et al., 2022). Therefore, the present study attempts to account the role of sub-tropical forests in Darjeeling, eastern Himalaya with an aim to assess the carbon stock and their sequestration potential.

2 Methodology

2.1 Study site

The present study was carried out in the sub-tropical forests of Darjeeling Himalaya. The study area (26°27′05″ to 27°13′10″ N latitude and 87°59′30″ to 88°53′ E longitude) is located on the north-western side of the Indian state of West Bengal. This region forms an integral part of eastern Himalaya hotspot and is bounded by Sikkim, Nepal and Bhutan on the north, west and east respectively. Due to wide array of altitudinal variation and climatic conditions, major vegetation types formed are tropical (up to 500 m), sub-tropical (500 – 1200 m), sub-temperate (1200 – 1850 m), temperate (1850 – 3200 m) and sub-alpine (above 3200 m).The climate in the region has four main seasons *viz.,* winter from December to February, spring and summer from March to May, monsoon or rainy season from June to August and autumn from September to November (Bhujel, 1996). The temperature varies within a minimum of 2.4°C to 9.6°C during winter, 8.3°C to 19.1°C during spring and summer and 12°C to 18°C during autumn season with an average annual precipitation of about 337.3 mm.

2.2 Data collection

The field study was conducted during 2021-2022. Stratified random sampling method was adopted for laying sampling plots within the forests. For vegetation analysis, 20 m × 20 m plots were randomly laid throughout the forests. Individuals of canopy within the plots were recorded and the circumference at breast height (CBH) was measured at 1.37 m above the ground using a diameter tape. The DBH of the individual tree species was ascertained using the formula, $\mathrm{DBH} = \mathrm{CBH}/\pi$.

For measuring the height of tree, Nikon rangefinder Forestry Pro II was used. The coordinates of the selected plots were noted with the help of GPS Garmin eTrex H. Tree taxa were identified with the help of floras (Cowan and Cowan, 1929; Hara, 1966, 1971; Ohashi, 1972; Grierson and Long, 1983, 1984, 1987, 1991, 1999; Noltie, 1994) and for correct nomenclature, World Flora Online was followed (WFO, 2022).

For phytosociological attributes, each tree species with DBH of ≥ 5 cm were considered. The trees were classified into different DBH classes viz. 5 – 15 cm, 15 – 25 cm, 25 – 35 cm, 35 – 45 cm, and >45 cm. Frequency (F), density (D), basal area (BA) and importance value index (IVI) of recorded tree species were estimated (Curtis and McIntosh, 1950; Philips, 1959; Misra, 1968). Diversity indices such as Shannon's index (H′) (Shannon and Weaver, 1963), dominance index (Cd) (Simpson, 1949), Pielou's equitability (E) (Pielou, 1966) and Menhinick's richness index (MeI) (Menhinick, 1964) were followed.

For sampling of litter fall, 50 cm × 50 cm subplots were deployed at regular intervals within the main plot (Devi and Yadava, 2010). From each subplot, fresh litters were collected and were segregated into leaf and non-leaf, their initial weights were obtained. About 200g of leaf and non-leaf litters each were separated and the litter samples were then oven dried at 70° C for 24 hours followed by taking dry weight.

Soil samples were also collected randomly from the sampling plots. The collected soil samples were labelled and taken to the laboratory in air tight polythene bags. Samples were then dried and was passed through 2 mm sieve and kept for further analysis. For estimation of soil bulk density, soil samples were cored at the depth 30 cm by using soil corer.

2.3 Estimation of biomass

2.3.1 Aboveground and belowground biomass

The aboveground biomass of trees was estimated by non-destructive method using generalized allometric model (Chave et al., 2014):

$$\mathrm{AGB\ (Mg)} =) 0.0673 \times (\mathrm{WD} \times \mathrm{H} \times \mathrm{D}^2)^{0.976}$$

where, WD is the wood density of species (g cm^{-3}), H is the height of individual trees (m) and D is the diameter of individual trees (cm). Compared with the aboveground biomass, tree root or the belowground biomass is more difficult to obtain, thus, it is estimated considering 20% of the above ground biomass (Mac Dicken, 1997).

2.3.2 Litter biomass

The biomass of litter was calculated as per Sheikh et al., (2017).

$$\text{Total dry weight (kg m}^{-2}) = \frac{\text{total fresh weight (kg)} \times \text{sub sample dry weight (g)}}{\text{sub sample fresh weight (g)} \times \text{sample area (m}^2)}$$

2.4 Estimation of biomass carbon

2.4.1 Aboveground, belowground and litter

Living biomass was calculated as the sum of aboveground and belowground components. The biomass of trees was converted to carbon stocks using the IPCC (2006) default fraction of 0.47. For the carbon content of litter samples, “loss of ignition” method was adopted. 5g of oven dried sample was taken in pre-weighted silica crucible. The crucibles were placed in an electronic muffle furnace at 550°C for 4 - 5 hours. After cooling, the crucibles with ash content were weighted and percentage of organic carbon was calculated (Ravindranath and Ostwald, 2008; Vaidya et al., 2017). The litter carbon (LC) was obtained by multiplying biomass of litter with carbon percentage determined (Taju and Marelign, 2022).

2.4.2 Soil organic carbon stock

From the collected soil samples, bulk density was calculated (Kalra and Maynard, 1991). Soil organic carbon (SOC) was examined by Walkley-Black rapid titration method (Walkley and Black, 1934). The soil organic carbon stock was calculated following Pearson et al., (2007).

$$\mathrm{SOC\ (Mg\ ha^{-1})} = [\rho_b \times \mathrm{d} \times \%\mathrm{C}] \times 100$$

where, ρ_b = soil bulk density (g cm^{-3}), d = depth over which sample is taken (cm), %C = concentration of carbon expressed in percentage.

2.5 Total carbon stock and sequestration potential

The total carbon stock of sub-tropical forests is the sum of carbon stock of the individual carbon pools. All the carbon stock was converted into CO_2 equivalents for which, biomass carbon stock has been multiplied with a factor of 3.67 (Pearson et al., 2007).

2.6 Data analysis

The analysis of vegetation parameters was performed using PAST version 4.03 (Hammer et al., 2001). The total aboveground biomass was calculated using “BIOMASS” package (Rejou-Mechain et al., 2017) and the correlation graphs were obtained using R software version 4.1.3 (R core team, 2022).

3 Results and Discussion

3.1 Species composition and diversity

Variations in the phytosociological attributes of the Himalayanforest ecosystems are mainly caused by varying environmental conditions, such as, topography, elevation gradients, species composition and soil condition (Dash et al., 2021). In the present investigation, a total number of 44 woody species within 35 genera under 22 families with 294 individuals were encountered from the studied area. The family Lauraceae represented 18% of the tree community followed by Fabaceae and Malvaceae (9%) each, Euphorbiaceae, Myrtaceae and Phyllanthaceae (7%) each whereas Combretaceae, Fagaceae and Meliaceae (5%). Families Anacardiaceae, Apocynaceae, Araliaceae, Burseraceae, Cornaceae, Cupressaceae, Juglandaceae, Lythraceae, Moraceae, Pandanaceae, Proteaceae, Simaroubaceae and Theaceae represented 2% each. The diameter distribution class of tree species is used to determine the population structure of forest stands (Rao et al., 1990). The diameter class distribution of individuals showed 140 individuals of trees within 5 – 15 cm, 63 individuals each under DBH 15 – 25 cm and 25 – 35 cm, and 24 individuals had diameter class above 35 cm (Fig. 1). The pattern of diameter class showed a decreasing trend with increase in diameter size.

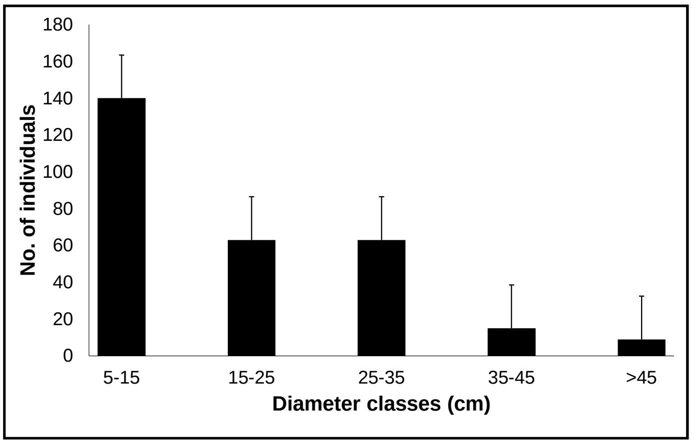

Fig. 1 DBH class distribution of tree species.

Density refers to the number of individual trees per unit area while basal area helps to determine the average amount of area occupied by the tree stems. A total tree density of 735 individuals ha^{-1} and total basal area of 11.923 ± 0.272 m^2 ha^{-1} was estimated for the tree taxa. The basal area shows significant negative correlation with tree density (Rawat et al., 2018). The estimated basal area lies in between values for the tropical forest in central India (Sahu et al., 2008). However, the value of tree density is higher than the value reported from the other subtropical forests of India (Sundriyal et al., 1994; Kharkwal and Rawat, 2010; Banday et al., 2017) and subtropical forest of Nepal (Paudel and Sah, 2015). Among them, *Litsea monopetala* and *Wrightia arborea* showed the maximum tree density (40 ind ha^{-1}) followed by *Duabanga grandiflora* (35 ind ha^{-1}), while *Ficus semicordata* and *Helicia nilagirica* showed minimum tree density (2.5 ind ha^{-1}). The highest basal cover was recorded for *Schima wallichii* (2.476 ± 0.018 m^2 ha^{-1}) followed by *Duabanga grandiflora* (1.434 ± 0.012 m^2 ha^{-1}) and the lowest was observed for *Reevesia pubescens* (0.007 ± 0.01 m^2 ha^{-1}).

The phytosociological structure of a species in a community is expressed through IVI that incorporates three parameters, relative density (RD), relative frequency (RF) and relative basal area (RBA) for measuring the overall ecological importance of species in its community (Thakur et al., 2021). The importance value index for the tree species ranged from 1.803 to 29.665 with maximum score for *Schima wallichii* (29.665) followed by *Duabanga grandiflora* (19.403) indicating these trees as dominant and co-dominant respectively, while the least IVI was for estimated for *Reevesia pubescens* (1.803). Similar results were estimated for sub-tropical forests of Senapati district, Manipur (Meetei et al., 2017).

The dominance-diversity curve is often used to interpret the community organization in terms of resource sharing and niche space (Whittaker, 1975). The curve illustratesthe role of certain species in determining community structure. The d-d curve revealed that *Schima wallichii* and *Duabanga grandiflora* are the dominant species andoccupies top positions and utilize major resources within community (Fig. 2). In ecology, diversity indices are key parameters for understanding the structure of forest ecosystems. Species diversity is defined as the quantitative measure of number of species and its abundance within a community. In the present study, the Shannon index (H′) was recorded as 3.588 and the Simpson’s dominance (Cd) value was 0.032. Malik and Bhatt, (2015) reports that Cd values mainly rely on the species richness of a community and higher richness of forest stand is determined by its low score. The Cd value is deeply impacted by the IVI of the top three important tree species in a community (Singh et al., 2016). The values of Pielou equitability and Menhinick index were 0.948 and 2.566 respectively.

Table 1 Quantitative characteristic of the recorded tree taxa.

Taxa		Family	D	RF	RD	RBA	IVI
Actinodaphne	*longipes*	Lauraceae	12.5	2.70	1.41	0.75	4.86
Actinodaphne	*sikkimensis*	Lauraceae	25.0	5.41	1.41	0.78	7.59
Ailanthus	*integrifolia*	Simaroubaceae	30.0	4.50	2.03	4.59	11.12
Alangium	*chinense*	Cornaceae	12.5	1.80	2.11	1.22	5.13
Albizia	*lebbeck*	Fabaceae	22.5	3.60	1.90	3.80	9.30
Albizia	*lucidior*	Fabaceae	17.5	1.80	2.95	3.08	7.84
Albizia	*procera*	Fabaceae	27.5	3.60	2.32	3.91	9.83
Baccaurea	*ramiflora*	Phyllanthaceae	7.5	0.90	2.53	0.74	4.17
Bischofia	*javanica*	Phyllanthaceae	7.5	1.80	1.27	0.52	3.59
Bombax	*ceiba*	Malvaceae	20.0	2.70	2.25	3.20	8.16
Brassaiopsis	*hainla*	Araliaceae	15.0	1.80	2.53	1.39	5.72
Bridelia	*sikkimensis*	Phyllanthaceae	12.5	2.70	1.41	0.38	4.49
Castanopsis	*indica*	Fagaceae	12.5	1.80	2.11	0.99	4.90
Castanopsis	*lanceifolia*	Fagaceae	17.5	1.80	2.95	2.58	7.33
Chisocheton	*cumingianus*	Meliaceae	10.0	0.90	3.38	0.33	4.61
Cinnamomum	*bejolghota*	Lauraceae	12.5	0.90	4.22	0.29	5.42
Cryptocarya	*amygdalina*	Lauraceae	12.5	1.80	2.11	0.64	4.55
Cupressus	*torulosa*	Cupressaceae	15.0	3.60	1.27	3.47	8.34
Drimycarpus	*racemosus*	Anacardiaceae	15.0	2.70	1.69	0.99	5.38
Duabanga	*grandiflora*	Lythraceae	35.0	5.41	1.97	12.03	19.40
Engelhardia	*spicata*	Juglandaceae	20.0	2.70	2.25	5.27	10.23
Erythrina	*variegata*	Fabaceae	12.5	1.80	2.11	1.93	5.84
Ficus	*semicordata*	Moraceae	2.5	0.90	0.84	3.28	5.03
Garuga	*pinnata*	Burseraceae	5.0	0.90	1.69	0.13	2.72
Helicia	*nilagirica*	Proteaceae	2.5	0.90	0.84	0.16	1.90

Kydia	*calycina*	Malvaceae	5.0	0.90	1.69	0.10	2.69
Litsea	*cubeba*	Lauraceae	17.5	1.80	2.95	0.71	5.46
Litsea	*monopetala*	Lauraceae	40.0	4.50	2.70	1.27	8.48
Litsea	*salicifolia*	Lauraceae	20.0	2.70	2.25	0.84	5.80
Macaranga	*denticulata*	Euphorbiaceae	17.5	2.70	1.97	0.38	5.05
Machilus	*parviflora*	Lauraceae	10.0	0.90	3.38	0.43	4.71
Mallotus	*repandus*	Euphorbiaceae	20.0	2.70	2.25	0.53	5.48
Ostodes	*paniculata*	Euphorbiaceae	27.5	3.60	2.32	1.09	7.02
Pandanus	*furcatus*	Pandanaceae	22.5	3.60	1.90	2.06	7.57
Reevesia	*pubescens*	Malvaceae	2.5	0.90	0.84	0.06	1.80
Schima	*wallichii*	Theaceae	55.0	2.70	6.19	20.77	29.67
Sterculia	*villosa*	Malvaceae	22.5	1.80	3.80	2.30	7.90
Syzygium	*nervosum*	Myrtaceae	7.5	0.90	2.53	1.75	5.19
Syzygium	*ramosissimum*	Myrtaceae	5.0	0.90	1.69	0.41	3.00
Syzygium	*tetragonum*	Myrtaceae	7.5	0.90	2.53	0.69	4.12
Terminalia	*chebula*	Combretaceae	10.0	1.80	1.69	3.13	6.62
Terminalia	*myriocarpa*	Combretaceae	15.0	1.80	2.53	4.78	9.11
Toona	*sinensis*	Meliaceae	7.5	0.90	2.53	1.41	4.84
Wrightia	*arborea*	Apocynaceae	40.0	4.50	2.70	0.84	8.04

D = density (individuals ha^{-1}); RF=relative frequency (%); RD=relative density (individuals ha^{-1}); RBA=relative basal area (m^2 ha^{-1}); IVI=importance value index (unitless).

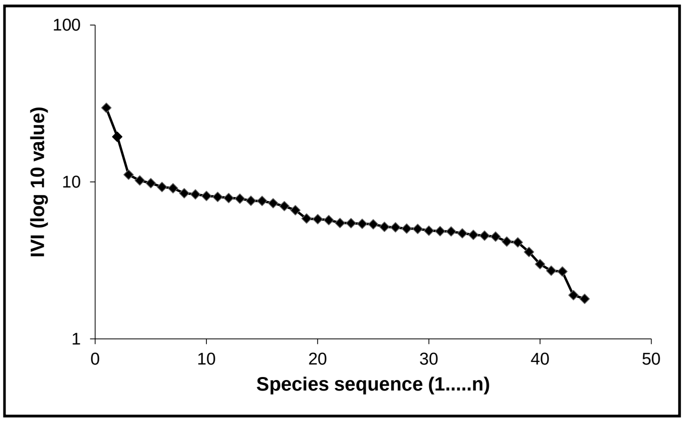

Fig. 2 Dominance- diversity curve for tree species in the study site.

3.2 Biomass

Biomass, in ecological terms, is the dry weight of live or dead matter from a woody plant, usually expressed as tonnes per area density. Aboveground biomass refers to the biomass above the soil surface that includes stems, bark, branches, seeds and stumps. Belowground biomass refers to root biomass (Ravindranath and Ostwald, 2008) while litter refers to the dead plant material fallen or that includes dead leaves, twigs, branches and bark (Pearson et al., 2005). The estimated AGB per tree ranged from 0.001 – 2.811 Mg ha^{-1} with a mean value of

0.306 Mg ha^{-1} while the total AGB ranged from 8.46 – 47.65 Mg ha^{-1} and the BGB ranged between 4.50 – 9.53 Mg ha^{-1}. The mean value of AGB was maximum in comparison to BGB with a mean of 4.50 Mg ha^{-1}. The mean value of AGB is comparable to some earlier findings (Singh et al., 1991; Devagiri et al., 2013). Out of 44 species enumerated, *Schima wallichii* accumulated greater biomass (21.38%) than other taxa in the study sites. The other most dominant species in terms of biomass were, *Duabanga grandiflora* (14.36%), *Terminalia myriocarpa* (9.72%), *Terminalia chebula* (5.55%), *Albizia lebbeck* (5.35%), *Ailanthus integrifolia* (4.87%), *Engelhardia spicata* (4.74%), *Castanopsis lanceifolia* (4.03%), *Cupressus torulosa* (3.09%) and *Bombax ceiba* (2.75%), jointly contributing 75.84% of the total AGB estimated.

Moreover, from the 294 individuals recorded, the mean AGB value of 0.306 Mg was estimated per tree. The biomass was observed highest in *Schima wallichii* (2.81 Mg $tree^{-1}$), followed by *Terminalia myriocarpa* (2.42 Mg $tree^{-1}$), *Duabanga grandiflora* (2.11 Mg $tree^{-1}$), *Terminalia chebula* (1.49 Mg $tree^{-1}$), and the least was recorded in *Castanopsis lanceifolia* (0.001 Mg $tree^{-1}$). The study of Tripathi et al. (2017) shows that *Schima wallichii* contains 19.56 Mg $tree^{-1}$ of AGB. According to Shrestha et al. (2016), *Schima wallichii* of sub-tropical forest has maximum potential for carbon sequestration. The low biomass range may be due to species composition, diameter class of trees, forest types and stand age (Singh and Verma, 2018).

3.3 Total carbon stock and sequestration potential

Carbon stock refers to the absolute quantity of carbon held at the time of inventory, whereas carbon sequestration is the process of removing C from the atmosphere and depositing it in a reservoir (Takimoto et al., 2008). The total carbon stock in the sub-tropical forest studied here was 33.53 Mg C ha^{-1}, the C value was well within the C range that have been reported from other sub-tropical forests (Banday et al., 2018 and Khan and Shaheen, 2022) and tropical forests (Salunkhe et al., 2014; Majumdar et al., 2016; Singh et al., 2016). The results revealed that most C was stored in tree standing biomass with AGB and BGB contributing 16.92 Mg C ha^{-1} (50%) and 3.38 Mg C ha^{-1} (10%), respectively. Soil as the second largest C stock after tree biomass accounted for 34% of total C stock. SOC content and C stock decreased with increasing soil depth and the soil C stock in the top layer accounted for more than one third of the soil C stock. Additionally, the contribution by litter (1.87 Mg C ha^{-1}) reflects them as the chief constituent of C stocks and thus should not be neglected in forest inventories. The amount of litter estimated is within the reported range of 0.16 – 3.26 Mg C ha^{-1} for Kolli forests (Mohanraj et al., 2011) and 0.26 – 2.64 Mg C ha^{-1} for sub-tropical forest (Sun and Guan, 2014). The percentage of carbon stock calculated is congruent to the value reported for temperate and subtropical mountain systems of Pakistan (Ali et al., 2020). The variation in the carbon stock of forest ecosystems may be due to forest age, forest types and topography (Dar and Sahu, 2018). Moreover, the amount of total CO_2 equivalent stored in the sub-tropical forest was estimated 123.048 Mg CO_2 ha^{-1} (Fig. 3).

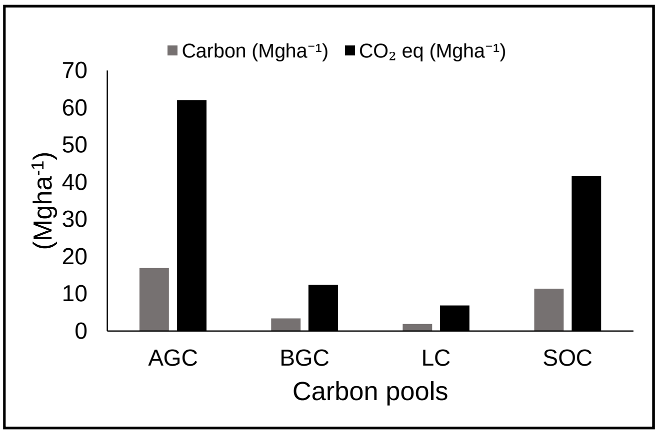

Fig. 3 Total carbon stock and carbon dioxide equivalent from study site.

3.4 Correlation of aboveground biomass with diameter, height and D^2H

The relationship between aboveground biomass with diameter (cm), height (m) and D^2H is shown in Fig. 4. The height and D^2H showed significant positive correlation with the AGB (R=0.618; 0.605), while diameter exhibited moderate correlation (R=0.586). Borah et al. (2013) and Poorter et al. (2015) stated that an old growth forests with enormous aboveground biomass, holds huge amount of their biomass in large areas. On the contrary, Terakunpisut et al. (2007) stated that pristine forest sequesters small amount of carbon because the matured trees slow down the growth. In the present study, trees with large diameter contributed more biomass and C stock, in congruence with the findings of earlier studies (Slik et al., 2013; Stephenson et al., 2014). Furthermore, the result reveals the significance of the maintenance and conservation of trees with large diameter and old growth forests (Lutz et al., 2018). Therefore, conserving old growth forests not just only assures greater carbon stocks, but also promotes conservation of biodiversity.

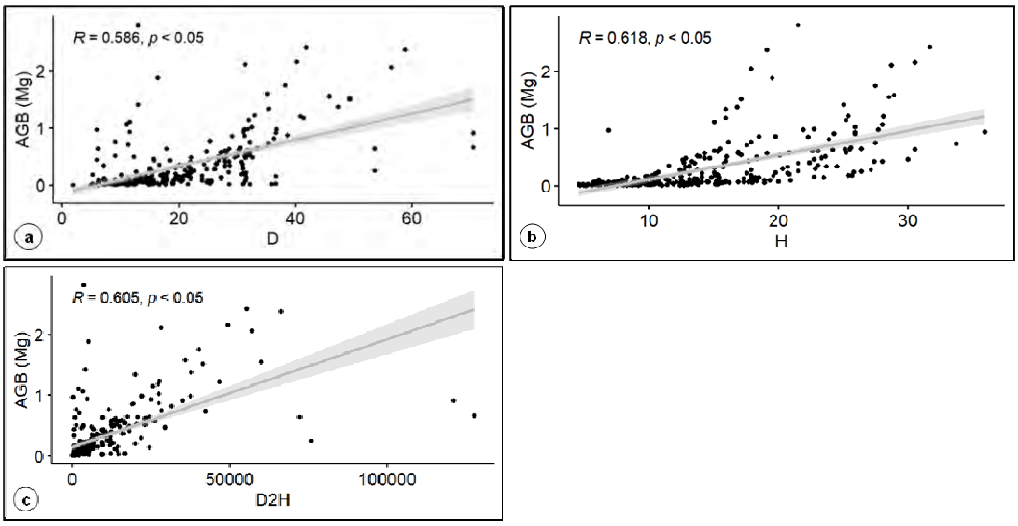

Fig. 4 Correlation of AGB with (a) diameter (b) height and (c) D^2H.

4 Conclusions

Information on the carbon stock is crucial for planning, management, and carbon sequestration in forestry. As, carbon sequestration is merely a consequence of biomass accumulation, the best method for the increment of carbon stocks is plantation (reforestation). The present study reveals that study site have the potential to increase the carbon pool in the biomass as well as in soil. The trees with large diameter were the major carbon storage. Tree like *Schima wallichii, Duabanga grandiflora, Terminalia myriocarpa, Terminalia chebula, Albizia lebbeck, Ailanthus integrifolia, Engelhardia spicata, Castanopsis lanceifolia, Cupressus torulosa* and *Bombax ceiba* accumulated greater biomass. Therefore, the present findings emphasize on the conservation of matured trees in the forests. The observed positive correlation of biometric measurements on biomass claims the need of maintenance and conservation of pristine sub-tropical forests in order to retain and increase the carbon storage capacity through appropriate sustainable management. Assessment of carbon stocks and sequestration potential plays a pivotal role in providing crucial information to develop suitable climate change mitigation and adaptation strategies.

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