Effects of Tree Species Diversity and Stand Structure on Carbon Stocks of Homestead Forests in Maheshkhali Island, Southern Bangladesh

Tarit Kumar Baul (tarit.ifes@cu.ac.bd)
University of Chittagong https://orcid.org/0000-0002-0805-0657
Avinanda Chakraborty
University of Chittagong Faculty of Science
Rajasree Nandi
University of Chittagong Faculty of Science
Mohammed Mohiuddin
University of Chittagong Faculty of Science
Antti Kilpeläinen
University of Eastern Finland Faculty of Science and Forestry: Ita-Suomen yliopisto Luonnontieteiden ja metsatieteiden tiedekunta
Taslima Sultana
University of Chittagong Faculty of Science

Research

Keywords: biomass, carbon stock, homestead forests, litterfall, soil, tree species

Posted Date: September 24th, 2020

DOI: https://doi.org/10.21203/rs.3.rs-78041/v1

Abstract

Background

This study aimed to estimate the carbon (C) stocks in homestead forest ecosystems (trees, litterfall, and soil) of Maheshkhali Island in Bangladesh and how tree species diversity and stand structural variation affected these C stocks. We randomly surveyed a total of 239 homestead forests proportionately allocating in hillside (67), beachside (69), and inland (103) in 2019 for measuring woody plants and sampling litterfall and C in soil at 0-30 cm depth. Tree (above- and below-ground) biomass was estimated by using pan-tropical allometric equations, and carbon of litterfall and soil were analyzed in a laboratory.

Results

We found a total of 52 tree species, of which, 41, 42, and 48 species were in the hillside, beachside, and inland, respectively, corresponding to the individuals of 840, 540, and 1504 sampled. According to the results, species diversity, richness, stand density, basal area (BA), and tree diameter at breast height (DBH) and height were significantly ($p \leq 0.05$) greater in the hillside and inland homestead forests, compared to the beachside. Most abundant species, for example, *Mangifera indica*, *Samanea saman*, and *Artocarpus heterophyllus* in the inland and hillside homestead forests stored most C in biomass, compared to the beachside forest. Tree biomass C stocks were 48-67% greater in the inland and hillside than on beachside forests due to significantly ($p \leq 0.05$) greater stand density, BA, and DBH. The overall C stock of litterfall was 0.1% of the total biomass carbon. C stock in soil surface was greatest in the hillside homestead forests due to the greatest litterfall. The total soil C stock was also affected by tree species, stand density and species richness, and their interaction with soil properties. Total soil C stocks across the depths were greatest (51 Mg ha^{-1}) in the inland homestead forests, with the greatest stand density and species richness.

Conclusions

Homestead forest ecosystems across the area stored total 96 Mg C ha^{-1}, which thus can contribute to climate change mitigation while generating C credit for small-scale homestead forests owners as well as conserving biodiversity in Bangladesh and countries alike.

1. Background

A gradual increase in the global emissions of carbon dioxide (CO_2) and consequent temperature increase has become a major concern to work on emissions mitigation [1-3]. Tropical forests play an important role in removing atmospheric CO_2 as they store one fourth of the global terrestrial C [4-6]. In addition, tropical forests support at least two-thirds of the world's biodiversity [e.g., 7] and have 50% of all known plant species, while their coverage from the total land area of the Earth is about 12% [8].

In Bangladesh, CO_2 emissions over the time are rapidly increasing, for example, 609% in 2017 (78 Mt of CO_2) compared to that of 1990 (11 Mt of CO_2) due to an increase in energy consumption [9, 10]. Bangladesh´s contribution to global emissions is very low; however, its carbon (C) rich forest ecosystems are highly affected by land-use change and adverse impacts of climate change [11], such as changes in precipitation and global sea level rise. Bangladesh has forest areas of about 2.53 million hectares, representing 17.5% of the total land area [12, 13]. These tropical forests are consisted of hill, mangrove, sal forests, and coastal mangrove plantations, with semi-evergreen and deciduous tree coverage. Natural hill and sal forests are being degraded due to illicit felling, shifting cultivation and conversion to other land uses [14, 15] . Apart from these natural and planted forests, tree outside forest (TOF) including homestead forests, roadside plantation is booming in Bangladesh [13].

The homestead forests of Bangladesh occupy 0.27 million hectares land area, representing 10% and 2% of the total forested land area and total land area, respectively [13, 16] and have potential to store C in biomass [17, 18]. The contribution of homestead forests to rural economy is second to agriculture and these forests provide people´s daily needs. The homestead forests of Bangladesh supply 70% of total timber and 90% of fuelwood and bamboo demand in the country [13, 19] and thus, release pressure on natural forests. The homestead forests can be characterized as well-established land use systems for sustenance and conservation of biodiversity [20], which are maintained by at least 20 million households. Since homestead forestry is practiced primarily for supplying daily necessities as a livelihood option, understanding the C stocks of the homestead forests is required to address their potential in climate change mitigation. The homestead forests in Bangladesh are in pressure due to fragmentation of landholdings [21] and not under the national forest management plan.

A few researches have estimated above-ground forest C stocks in Bangladesh. C stocks were found to vary with land uses, including mangrove and coastal (99 Mg C ha^{-1}; [22]), protected contiguous and fragmented (34-53 Mg C ha^{-1}; [15]), bamboo (53 Mg C ha^{-1}; [23]), hill (103 Mg C ha^{-1}; [16]) and homestead (53 Mg C ha^{-1}; [17]) forests. These C stocks have been found to be dependent on the stand structure (e.g., tree height, DBH, density, basal area) [24, 25] and tree species [26, 27], and stands with fast-growing tropical tree species having the highest forest C stocks (201 Mg C ha^{-1}; [28]). Tree species diversity may increase above-ground biomass C stocks of tropical forests [29, 30] .

The C stock in litterfall is only a small fraction relative to above-ground biomass C in forest ecosystems [31], but this needs to be studied when estimating C dynamics among pools [32]. A balance between accumulation and decay of litter controls the accumulation of organic matter in an ecosystem [33]. Within the same climate, forest and tree species types are the main drivers of the litterfall, e.g., in mixed species natural forests and planted forests [34]. Litterfall is also affected by the management such as tree harvest and pruning [35-37]. Research on C stock in litterfall has been very scarce in the homestead forest of Bangladesh, and generally in tropical and temperate forests [38].

In Bangladesh, soil C concentration has been found variable (1-16 mg g^{-1}), mainly responsible to the site and depth in soil [39, 40]. Soil C stocks estimated in Bangladesh were 23 Mg C ha^{-1} in semievergreen [41], 34 Mg C ha^{-1} in mangrove [22], and 59 Mg C ha^{-1} in deciduous [42] forests. Earlier, changes in stand structure and litter quality have found to modify the soil C dynamics in agroforestry ecosystems and also in tropical homestead forests [43-46]. The dynamics are also influenced by microclimatic and edaphic conditions [47-49] and they vary in space and time [50]. For instance, tree size, stand density and species richness positively affected soil C in tropical forests [51, 52]. While significant advances in estimating the C balance of forests have been attained, there are still critical uncertainties in the magnitude of soil C stocks [37].

The United Nations Framework Convention on Climate Change (UNFCCC) introduced two mitigation instruments, clean development mechanism (CDM) and reducing emissions from deforestation and degradation of forests and conservation and enhancement of forest C stock with sustainable management (REDD+) [2, 53, 54]. However, the lack of reliable estimation of tropical forests C stocks may hinder the successfully implementation of REDD+ and similar mechanisms [55]. More importantly, REDD+ takes only large-scale forests into account, while ignoring the small-scale forestry, such as homestead forests [56]. The evidence of carbon sequestration potential of TOF is crucially significant for small-scale forest landowners or households in developing countries, such as Bangladesh, as it´s national strategy is in line with international treaties of the Paris agreement 2015 and the Kyoto Protocol 2001. In addition to the Bangladesh Forest Department (BFD) managed natural and planted forests, the estimation of the C stocks in homestead forests is imperative for investigating their potentials for C enhancement and credits [56, 57].

Under this circumstance, the study about homestead forests for estimation of C stocks would be the scientific-based information for the policymakers and scientists with a view to supporting climate change mitigation efforts. Our study aims to estimate the C stocks in homestead forest ecosystems (trees, litterfalls, and soil) of Maheshkhali Island under Cox's Bazar District in Bangladesh and how tree species diversity and stand structural variation affect these C stocks.

2. Materials And Methods

2.1 Study area

The study was conducted in homestead forests of Maheshkhali Island under Cox's Bazar District, a coastal area of Bangladesh (Fig. 1), emerged as most vulnerable to climate impacts as documented in the recently published report of the World Bank (WB) [11]. Maheshkhali island is the only hilly island with complex geological system on the eastern cliff coast of Bangladesh, bounded by coastal plain characterizing inimitable geologic, tectonics and geomorphologic particularities [58], located between 21°28' and 21°46' N latitude and 91°51' and 91°59' E longitude [59]. It is bordered on the north by Chakaria Upazila (sub-district), on the south Cox’s Bazar Sadar Upazila and the Bay of Bengal, on the east Chakaria and Cox's Bazar Sadar Upazilas, and on the west Kutubdia Upazila and the Bay of Bengal (Fig.

1). It occupies an area of 362.18 km^2, with a total of 33287 households [60]. The island has a moist tropical climate with a long wet season (April–October) and a relatively short dry season (November–March). The mean annual precipitation, temperature, and relative humidity are 3,627 mm, 25.7 ^oC, and 70 to 90 %, respectively [61]. This region is prone to cyclonic storms, tidal surges, and flood due to proximity to the Bay of Bengal, a source of cyclones, usually occurring during April–May and October–November. The island was separated from the mainland by severe cyclone and tidal bore of 1559 [62].

The island has four subdivisions including active, young, and old coastal plain, and hilly areas with piedmont plain. Geological deposition of sedimentation forms landmasses [58]. Maheshkhali with an accretion rate of 1.2 sq. km. per year since 1972 formed huge landmasses in the southwest coastal plain (e.g., Bara Maheshkhali) and western coastal plain (e.g., Gorakghata) [63], contributing to the land use and land cover changes. The major land uses include salt cultivation, agricultural land, hill forests and coastal forests, which have been changed markedly since 1972. Expansion of salt fields caused a decline in the agricultural land at an average rate of 14.5 hectares per year, and extensive and illegal hill cutting for settlement, betel leaf cultivation, and unpanned development caused reduced hill forests at an average rate of 90 hectares per year [59]. The coastal forests are in an increasing trend due to the planting mangrove trees by the BFD and local people along the eastern and western coast to protect lives and properties from the adverse impacts of cyclonic events and floods. However, shrimp cultivation, another type of land use threatened the coastal forests, to some extent, especially old coastal zone [59].

BFD manages its hill and coastal forests consisting of mangrove plantations of 534.54 ha and 8129.9 ha and non-mangrove plantations of 2667.3 sq. km and 232.66 sq. km, under two range[1], Maheshkhali and Gorokghata, respectively [64]. Forest covers several hills of up to 23 m and the low-laying valleys. Soils of the forest vary from clay to sandy loam and to some extent yellowish red sandy clay, with low pH. Hills are mainly composed of sands and various stones, including limestone, siltstone, and mudstone [65]. Peoples` dependence on hill forests were significant for collecting fuelwood, house and boat making materials, traditional medicine, and non-timber forest products such as bamboo honey, fodder etc. However, from the time immemorial, this overexploitation of the resource declined in biodiversity in the area [66]. The detrimental activities included deforestation, hill cutting for converting forest land to settlement and agriculture, and coastal forests to shrimp culture and salt fields [66]. This situation made the individuals for taking care and managing homestead forests very carefully for their protection from coastal storms, surges, floods. BFD has no management and administrative right over homestead forests as they are managed by owners themselves.

Fig. 1 Map of a) Bangladesh and b) Maheshkhali Island showing three categorized study sites with c) sampling points of homestead forests.

2.2 Reconnaissance survey

Before starting the data collection, three initial field visits for reconnaissance survey were made to get an overview of the study area in February 2019. This included observation of general conditions including geographical location, physiography, hill and coastal forests, and homestead forests of the area. We divided three Unions[2] Chhato Maheshkhali (recently converted as municipality), Gorokghata, and Bara Maheshkhali as the hillside, beachside, and inland, respectively, under Maheshkhali sadar Upazila according to the geographic location (Fig. 1). Then the researchers visited to the respective administrative (Union Parishad) offices of these three Unions to collect relevant data of villages, number of households and homestead forests of each village. Additionally, we interviewed the Chairman of these three Unions as key informants to gather knowledge about the study sites and as well as inform them about the purpose of the study.

2.3 Sample selection and woody vegetation measurement in homestead forests

Settlement is an important type of land use, and the population density was relatively higher in the hillside (Chhato Maheshkhali), beachside (Gorokghata), and inland (Bara Maheshkhali) compared to the northwestern part of the island [67]. From the key informant (KI) interview with the Chairman of the Union in February 2019 it was known that some of the settlements started in the foot of the hills under the hillside by human intervention in modifying slope of the hills. Since after the loss of lives in 1991 cyclone, people started migrating from Gorakghata to other places [63]. Settlement started earlier in the inland site and population was relatively higher [67]. Settlement was assumed to be associated with the homestead forests in the three sites. The homestead forests of these three sites were also assumed to represent the same kind of ecotype. We hypothesized that C stocks of the homestead forests differ from each other among the three sites.

The sampling procedure followed from Upazila to Union, Union to village, village to homestead forests of the households. From the lists of the number of households provided by the office, with a sampling intensity of 5% as accepted by the United nations [68], a total of 239 homestead forests were determined. Then, based on the total number of households in each of the three sites, 67, 69, and 103 homestead forests from hillside, beachside, and inland, were randomly allocated for the study in Maheshkhali sadar Upazila in 2019 (from February to April). The mean area of the studied homestead forests in these three sites were 0.02, 0.01, and 0.02 ha per household.

Each of the homestead forests was divided into quadrats (5m × 5m) based on the area and the direction from the dwelling. The surveyed data were recorded which included all woody plants identification, with measurement of height (m), diameter at breast height (DBH, cm) and the area of the homestead forests. The owners of the homestead forests helped in identification with local name, and in few cases, herbarium was prepared to ensure the identification with scientific names. The height measurement was made by rangefinder and DBH by diameter tape. The coordinates of each point of sample collections was recorded by using GPS. Herbs and shrubs were not considered as 98% of total forest biomass consists of tree biomass; they may be ignored in estimation of carbon [25]. Homestead forests are well managed and therefore, are usually free from herbs and lianas.

2.3 Soil and litterfall sampling for estimating C stock

A sampling of the litterfall was made in 4 points wherever available for each of the three different sites in 2019 (from February to April), thus making a total of 12 (3 × 4 = 12) samples. All litterfalls at each point of an area of 1 m^2 (1 m × 1 m) was collected using a metallic frame. A pit of 30 cm depth, under the litterfall layer sampling point, was dug by using a soil auger and mineral soil samples were collected at 10, 20, and 30 cm depths. This procedure was followed for four samples consisting of 12 (4 × 3 depths = 12) subsamples for each of the three different sites, thus making a total of (12 × 3 = 36) subsamples. Accordingly, following the same procedure, 36 unaltered soil subsamples were collected using a core (10 cm high and 6.5 cm wide) to measure bulk density (BD) at the same three depths in each point, following Blake (1965) [70].

2.4 Data analyses

2.4.1. Estimation of tree (above- and below-ground) biomass, and density and basal area of stands

Above-ground biomass (AGB) was estimated by converting tree data into biomass using allometric Equation (1), (2), (3), and (4) for tropical trees, *Cocos nucifera*, *Areca catechu*, and *Phoenix dactylifera*, respectively (Table 1). Below-ground tree biomass (BGB) was estimated as 15% of AGB [74]. Tree total biomass (TB) was the summing up of AGB and BGB. Finally, total C stock (Mg ha^{-1}) was estimated as C content is assumed to be 50% of dry TB [75]. To estimate AGB wood density (g cm^{-3}), a required variable, which was collected from Bangladesh Forest Research Institute (BFRI) [76]. For those not found in BFRI publications we used global wood density database [77, 78]. Additionally, species level C was also estimated for most frequent tree species and expressed in kg C per individual across three sites. Stand density (D) (individual ha^{-1}) and basal area BA (m^2 ha^{-1}) were estimated (Equations 5 and 6). Mean values of tree biomass, density, and BA were compared among three different homestead forest sites.

2.4.2. Laboratory analysis and estimation of carbon of litterfall and mineral soil and bulk density (BD)

To estimate soil organic carbon (SOC), washed silica crucibles were dried in an oven at 105 °C for half an hour and cooled in desiccators, and then weight was taken. Dried soils were ground by pestle and then exactly 5 g of grind soils were kept in silica crucibles and weighted by an electric balance. The crucibles with soil were then transferred to an electric muffle furnace for igniting at 850 °C for one and half an hour. Then crucibles with soils were cooled in the desiccator and reweighted to determine the percent loss of ignition LOI (%), from which, SOC (%) was calculated (Equations 7 and 8). C stocks in mineral soil at three depths were calculated using BD (g cm^{-3}) (Equation 9) and expressed in Mg ha^{-1} for three different sites (Table 1). We calculated soil BD as the quotient between the dry mass of the fine fraction in the core segment and volume of the cylinder [82].

To estimate the biomass of litterfall, after taking the fresh mass of the original samples collected from each point of litter collection, adequate subsamples from the weighted original sample were made and labelled. In each plot, the number of original samples was four and subsamples three to five, depending on the wet masses of the original samples. The wet masses of all the subsamples were measured and recorded. Subsamples were oven-dried at 65 ºC until reaching a constant mass and dried masses were recorded. Then, the dry mass of the original sample from the wet to dry ratio of the subsamples was estimated (Table 1; Equations 10 and 11). The C concentration was considered to be 44.36% of the dry mass of litter [83]. The process was repeated for all 12 original samples collected from homestead forests across three different sites. C stocks in litterfall were calculated and expressed in kg C ha^{-1} for three different sites. These C concentrations and stocks of litterfall and soils were compared among three different homestead forest sites.

2.4.3 Estimation of tree species richness, diversity and relative frequency and relative density

Tree species richness (Margalef index) and diversity (Shannon-Weiner Index, H) were estimated according to Equations 12 and 13 (Table 1). The greater value of indices of diversity indicates greater species richness and diversity in an area. In addition, the relative frequency of occurrence (RF %) and relative density (RD %) for species were estimated (Equations 14-16). Mean values of tree height (m), DBH (cm), all indices, RF, and RD were compared among three different sites.

2.4.4 Statistical analyses and modelling work

One-way analysis of variance (ANOVA) was used to determine whether there are any statistically significant differences ($p \leq 0.05$) between the three homestead forest sites in tree biomass (Mg C ha^{-1}), height (m), DBH (cm), density (individual ha^{-1}), basal area, BA (m^2 ha^{-1}), Margalef richness index and Shannon-Wiener diversity index. Tukey´s post hoc tests were performed to determine which site significantly differed from the other sites. Moreover, two-way analysis of variance (ANOVA) was performed to determine whether there are any statistically significant differences ($p \leq 0.05$) of soil C stock (Mg C ha^{-1}) against three sites and three soil depths.

Relationship between tree biomass (Mg C ha^{-1}) and a) height (m), b) DBH (cm), c) density (individual ha^{-1}), d) basal area, BA (m^2 ha^{-1}), e) Margalef richness index, and f) Shannon-Wiener diversity index were modelled by using linear regression analysis. In addition, multiple regression analysis was used to model the effect of all variables (a-f) to tree biomass.

3. Results

3.1 Structural composition in homestead forests

3.1.1 Tree height and DBH

We found the greatest mean tree DBH and height in the hillside and lowest in the beachside homestead forests, with significant ($p \leq 0.05$) differences among the three sites (Table 2). The greatest number of trees were in 16-20 cm DBH class, with the inland homestead forests site being dominated. The trees with large DBH (31-45 cm) were greater in the inland compared to the other two sites (Fig. 2a). However, there were only few trees with DBH less than 15 cm due to the harvesting of those at pole stage to be used as fuels. Related to height, the greatest number of trees were in 6-9 m class. Taller trees (10-13 m) were greater in inland and hillside homestead forests (Fig. 2b).

3.1.2Species diversity and richness

The tree species diversity and richness of homestead forests were significantly ($p \leq 0.05$) greater in the hillside and inland, compared to those on the beachside (Table 2).

3.1.3 Stand density and basal area (BA)

Mean stand density and BA of homestead forests were 601 individuals ha^{-1} and 27 m^2 ha^{-1}, respectively across the study area. Regarding the site, stand density in the inland homestead forests was significantly ($p \leq 0.05$) greatest, compared to that in the other two sites, while no significant difference in these two (Fig. 3). BA of homestead forests was significantly ($p \leq 0.05$) greater in the inland and hillside, compared to that of other one (Fig. 3).

Fig. 3 Stand density (primary y axis) and basal area (secondary y axis) in the homestead forests. Bars represent standard error of mean.

3.1.4Relative frequency and relative density of tree species

Among 52 tree species found in the homestead forests, the numbers of species in the hillside, beachside, and inland were 41, 42, 48, respectively (Table 3). The number of tree individuals sampled were 840, 540, and 1504, respectively. The most five frequent species across the area were *Mangifera indica, Acacia auriculiformis, Cocos nucifera*, *Artocarpus heterophyllus*, and *Samanea saman* and these also corresponded to the RD (Table 3).

3.2 Tree (above-and below-ground) biomass and litterfall carbon in homestead forests

Mean tree (above-and below-ground) biomass in the homestead forests was estimated to be 46.11 Mg C ha^{-1} across the study area. Tree biomass was significantly ($p \leq 0.05$) greater in the hillside and inland, compared to that in the beachside homestead forests (Fig. 4). The mean dry biomass of the litterfall was 44.52 ± 9.67 kg C ha^{-1} across the study area. These were 60.75 ± 20.65, 39.61 ± 8.55, and 33.21 ± 19.78 kg C ha^{-1} in the hillside, beachside and inland, respectively.

Among the species, *Samanea saman* dominated in storing C, with *Mangifera indica*, *Artocarpus heterophyllus*, *Diptercarpus turbinatus*, and *Albizia procera* stored relatively greater amount of biomass C in the inland and hillside homestead forests, compared to the beachside forest (Fig. 5).

3.3 Carbon concentration and stocks in mineral soil

C concentration and stocks diminished with increasing depth of soil in homestead forests across three sites (Table 4; Fig. 6). The greatest mean C stocks were found throughout the soil depths in the inland homestead forests. However, C stocks did not significantly ($p \leq 0.05$) vary with sites and with soil depths (Fig. 6). The bulk density of soils increased with depth for all sites (Table 4).

3.4. Relationship of tree biomass with structural compositions in homestead forests

Figure 7 shows the significant ($p \leq 0.05$) relationship between tree biomass (Mg C ha^{-1}) and height (m), DBH (cm), density (individual ha^{-1}), basal area, BA (m^2 ha^{-1}), Margalef richness index, and Shannon-Wiener diversity index in the homestead forests across three sites. Multiple regression analysis reveald that 90% of the variability in biomass C was explained by these factors together.

4. Discussion

Taking urgent action to combat climate change and its impacts are amongst the Sustainable Development Goal 13, which provides us with a common plan and agenda to tackle climate change. Forest-based mitigation, such as storing C in an ecosystem helps in removing CO_2 emissions from the atmosphere. This requires growing trees in and outside the large-scale forestry, for instance in homestead forests. Realizing this potential, this study estimated the C stocks in the homestead forest ecosystems in an Upazila of Maheshkhali island, a hilly and coastal area in Southern Bangladesh, and estimated how tree species diversity and stand structural variation affect these C stocks.

Mean biomass C stock estimated (46 Mg C ha^{-1}) in our case was close to that found (54 Mg C ha^{-1}) in homestead forests in northern Bangladesh [17]. This, however, is lower than that found in the mangrove (99 Mg C ha^{-1}; [22]) and entire forests (49-121 Mg C ha^{-1}; [12]) of Bangladesh. This disagreement could be explained by the lower overall species diversity and richness in our study, which indicates lower biomass C stock [15]. For example, Nath et al. (2015) [18] estimated tree biomass of 118 Mg C ha^{-1}, with a diversity index of 2.21 in homestead forests, whereas in our case the index was 1.24. However, we found the significantly positive effects of tree species diversity and richness on biomass C stock. Greater species richness and diversity index in the inland and hillside homestead forests indicated higher above- and below-ground biomass C stocks compared to that in the beachside. An increase in species richness and diversity index by one unit increased the biomass C stock by 22 and 30 Mg C ha^{-1}, respectively (Figures 7e and 7f). Our findings agreed with earlier studies in tropical forests of Asia and Africa [29, 30, 88], implying the more tree species diversity and richness the more likely higher above-ground biomass C stock.

Our study revealed a greater contribution of some of the frequently occurred species to the total C stocks. The relatively greater number of individuals of *Mangifera indica*, *Samanea saman*, *Artocarpus heterophyllus*, and *Dipterocarpus turbinatus* in the inland and hillside homestead forests, contributed to the greater C stocks compared to the beachside. Alamgir and Al-Amin (2007) [26] also found a greater biomass C stock in these tree species in the hill forests of Bangladesh. The strongly positive effects of BA and stand density on biomass C stocks are also generally in line with the findings of [89] who reported that greater density (4258 ha^{-1}) and BA (53 m^2 ha^{-1}) increased biomass C stocks in roadside plantations.

In this study, with greater DBH and height, above- and below-ground biomass C stocks were 48-67% greater in inland and hillside homestead forests than in beachside forests. The overall share of individuals with DBH of 31 – 40 cm was also greater in the hillside and inland homestead forests which contributed to the greater above- and below-ground biomass C stock in comparison with that of the beachside. In our case, when tree height and DBH increased by one unit each, the biomass C stock increased by 11 and 3 Mg C ha^{-1}, respectively (Figures 7a and 7b). The importance of contribution of larger trees to the biomass C stock is in line with [24] who depicted that individuals with DBH of 10 – 56 cm, constituting only 28% of stand density, contributed 84% of the total biomass C stock in mangrove forest.

The C stocks of tropical litterfall have not received much attention in research as it constitutes a small fraction of above-ground biomass [32, 90] . The overall C stored in litterfall was 0.1 % of the total biomass C in this homestead forest, while it was 1.8 % in the natural forests of Bangladesh [34]. The C stock in litterfall was greatest in the hillside, which was up to 53–83 % greater than that in the beachside and inland homestead forests. Litter accumulates in natural forests as they are no longer under silvicultural management due to the harvesting restriction, while litters in homestead forests are used as cooking fuel [91, 92], which leads to lower C stocks.

There was a clear decline in soil C concentration and stocks across three homestead forest sites. Total soil C stock in the inland homestead forests across the three depths was greatest (51 Mg ha^{-1}), with increased stand density and species richness. The greater C in soil was correlated with greater stand density, and species diversity and richness, which has been found earlier in tropical agroforestry systems [46, 52] and temperate forests [43, 93]. The surface soil had 5-38% and 29-75% greater C stock of that stored at a depth of 20 and 30 cm, respectively, depending on the site. Hillside forests with greater litterfall, had 8-9% greater surface soil C stock compared to beachside and inland forests. Acacia and Mahagani species were abundant in the hillside and inland forests, contributing to soil C storage. This was because, Acacia and Mahagani litters were not preferred as fodder or fuels due to being small leaflet and unpalatable, contrary to *Mangifera indica* and *Artocarpus heterophyllus* [35]. Acacia species planted site in Bangladesh and African Mahogani in Ghana were found enhancing soil C stock [35, 41, 94]. Earlier studies on homestead forest and agroforestry in India also reported that the slower decay rate of Acacia and *S. mahagoni* litters resulted in accumulation of organic matters in the soil, compared to *M. indica, A. heterophyllus and Anacardium occidentale* [44, 95].

5. Policy Implications And Conclusions

The hillside and inland homestead forests stored remarkable amount of tree biomass C, which was significantly increased with increasing stand density, BA, DBH, height, species richness and diversity. A smaller C stocks in litter found in our study compared to earlier studies could be linked to the removal of litter for using it as fuels. Higher litterfall in the hillside homestead forests may have contributed to surface soil C stocks, but the overall soil C stock in the study was also affected by types of litter of species, the stand density, and species richness. However, the decay of litter and humus and underground process in tropical forests influencing soil C stock, depending on environmental factors, would need to be studied in further.

In Bangladesh, total emissions are 78 Mt of CO_2 [9]. Conversely, the land use and land use change and forestry (LULUCF) sector´s C sink was 81 Mt in 2010 [96]. According to our study, the homestead forest ecosystems (trees, litterfall and soil) store 96 Mg C ha^{-1}, which is 73 and 62% of that found in mangrove and hill forests (133 and 154 Mg C ha^{-1}, respectively [16, 22]. This can be upscaled to be 26 Mt considering total homestead forest area of the country, which thus can contribute to climate change mitigation through REDD+ and CDM mechanisms as emphasized in UNFCCC's mitigation strategies [2, 97].

This study reduced the gap with documentation and producing estimated C of homestead forests that would help for applying REDD+ mechanism since the contribution of TOF in C sequestration is ignored due to the scarce documentation [57]. In addition, the empirical and analytical results of this study could be a source of C credits through Payment for Environmental Services (PES) for small-scale homestead forests owners or households in developing countries, such as Bangladesh while generating livelihood options and biodiversity conservation [56, 57].

Abbreviations

AGB: above ground biomass; BGB: below ground biomass; BA: basal area; BD: bulk density; C: carbon; DBH: diameter at breast height; LOI: loss of ignition; RF: relative frequency; RD: relative density; SOC: soil organic carbon; TB: total biomass; TOF: tree outside forest;

Declarations

Authors' contributions

All authors have contributed significantly to produce this manuscript. TKB has made research conception and design, analyses, and interpretation of data and been involved in preparing and revising the manuscript. AC has been in field survey and organizing field data and involved in analyses of soil and litter data in the lab. RN has been involved in research conception, design of data acquisition and been involved in revising the manuscript. MM has been involved in drafting or revising the manuscript critically. AK has made substantial contribution with editing and revising the manuscript critically. TS has been involved in analyses of soil and litter data in the lab. All authors have read and approved the final manuscript.

Acknowledgments

Authors would like to acknowledge the Research Cell and Publication office of University of Chittagong, Bangladesh for providing research grant. Authors are highly thankful to the homestead forest owners for the permission to survey their forests and giving us valuable time during survey. In addition, concerned officers of the local government and Forest Department offices in the study area are greatly acknowledged for providing us with valuable information related to the study.

Funding

This research work was funded by the Research Cell and Publication office of University of Chittagong, Bangladesh.

Competing interests

The authors declare that they have no competing interests

Availability of data and materials

All data generated or analysed during this study are included in this article.

Consent for publication

Not applicable

Ethics approval and consent to participate

Not applicable

Author details

[1] Institute of Forestry and Environmental Sciences, University of Chittagong, Chittagong 4331, Bangladesh

[2] University of Eastern Finland (UEF), Faculty of Science and Forestry, School of Forest Sciences

P.O. Box 111, FI-80101 Joensuu, Finland

References

1. IPCC: Climate change. 2014. Mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change. 2014. http://www.ipcc.ch/. Accessed 20 Mar 2020
2. IPCC: Summary for policymakers 2018. In: Zhai, P., Pörtner, H.O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Pean, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T. (Eds.), Global Warming of 1.5 oC. An IPCC Special Report on the Impacts of Global Warming of 1.5 oC above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global

Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty [V. Masson-Delmotte. World Meteorological Organization, Geneva: Switzerland; 2008. p. 32

3. UNFCCC. Adoption of the Paris Agreement. Geneva: Switzerland; 2015. p. 32
4. Adame MF, Kauffman JB, Medina I, Gamboa JN, Torres O, Caamal JP, Reza M, Herrera-Silveira JA, Carbon stocks of tropical coastal wetlands within the karstic landscape of the Mexican Caribbean. PloS One 2013;8:565-569
5. Dixon RK, Brown S, Houghton RA, Solomon AM, Trexler MC, Wisniewski J. Carbon pools and flux of global forest ecosystems. Science 1994; 263:185–190
6. Mitchard ETA. The tropical forest carbon cycle and climate change. Nature 2018;559:527-534
7. Wilson EO, Peter FM, Raven PH. Our diminishing tropical forests. In: Wilson EO, Peter FM, editors. Biodiversity. National Academy Press, Washington, DC; 1988.
8. Ashton MS, Tyrrell ML, Spalding D, Gentry B. Managing forest carbon in a changing climate. Springer Science & Business Media; 2012
9. Sarkar MSK, Sadeka S, Sikdar, MMH, Badiuzzaman, Energy Consumption and CO2 Emission in Bangladesh: Trends and Policy Implications. Asia Pac. j. energy environ. 2015;2(3)
10. IEA (International Energy Agency): https://www.iea.org/countries/Bangladesh (2020). Accessed 22 Jun 2020.
11. Mani M., Bandyopadhyay S, Chonabayashi S, Markandya A, Mosier T. South Asia’s Hotspots: The Impact of Temperature and Precipitation Changes on Living Standards, South Asia’s Hotspots: The Impact of Temperature and Precipitation Changes on Living Standards. https://doi.org/10.1596/978-1-4648-1155-5. (2018) Accessed 22 Jun 2020.
12. Alamgir M, Turton SM. Climate change and organic carbon storage in Bangladesh forests. In: Tuteja N, Gill SS, editors. Climate change and plant abiotic stress tolerance. Wiley-VCH Verlag; 2014
13. BFD (Bangladesh Forest Department): http://www.bforest.gov.bd/ (2020). Accessed 23 Mar 2020.
14. Hansen MC, Potapov PV, Moore R, Hancher M, Turubanova SA, Tyukavina A, et al. High-Resolution Global Maps of 21st-Century Forest Cover Change. Science, 2013;342:850-853.
15. Islam M, Deb GP, Rahman M. Forest fragmentation reduced carbon storage in a moist tropical forest in Bangladesh: Implications for policy development. Land use policy 2017;65:15–25. https://doi.org/10.1016/j.landusepol.2017.03.025
16. Mukul SA. Biodiversity conservation and ecosystem functions of indigenous agroforestry systems: Case study from three tribal communities in and around Lawachara National Park. In: Chowdhury MSH, editor. Forest Conservation in Protected Areas of Bangladesh: Policy and community development perspective. Springer, Switzerland; 2014. p. 171-179
17. Jaman MS, Hossain M F, Shariful I, J Helal MG, Jamil M, Mizanur R. Quantification of Carbon Stock and Tree Diversity of Homegardens in Rangpur District, Bangladesh. Int J Agric For [Internet]. 2016;6:169–80. Available from: http://journal.sapub.org/ijaf

18. Nath TK, Aziz N, Inoue M. Contribution of Homestead Forests to Rural Economy and Climate Change Mitigation: A Study from the Ecologically Critical Area of Cox's Bazar—Teknaf Peninsula, Bangladesh. Small-scale For. 2015;14:1–18.
19. Singh CD. Valuation and evaluation of trees outside of the forest (TOF) of Bangladesh. Draft paper for a regional study for Asia and Pacific in contribution to the forest resource assessment (FRA). Rome: FAO; 2000.
20. Kabir ME, Webb EL. Can Homegarden conserve Biodiversity in Bangladesh?, Biotropica 2008;40 (1):95-103
21. Motiur RM, Furukawa Y, Kawata I, Rahman MM, Alam M. Role of homestead forests in household economy and factors affecting forest production: a case study in southwest Bangladesh. J For Res. 2006;11:89–97. DOI 10.1007/s10310-005-0191-6
22. Mizanur Rahman M, Nabiul Islam Khan M, Fazlul Hoque AK, Ahmed I. Carbon stock in the Sundarbans mangrove forest: spatial variations in vegetation types and salinity zones. Wetl Ecol Manag. 2015;23:269–83.
23. Sohel MSI, Alamgir M, Akhter S, Rahman M. Carbon storage in a bamboo (Bambusa vulgaris) plantation in the degraded tropical forests: Implications for policy development. Land Use Policy, 2015;49:142–151. http://dx.doi.org/10.1016/j.landusepol.2015.07.011
24. Kamruzzaman M, Ahmed S, Paul S, Rahman MM, Osawa A. Stand structure and carbon storage in the oligohaline zone of the Sundarbans mangrove forest, Bangladesh. Forest Sci Technol [Internet]. Taylor & Francis; 2018;14:23–8. Available from: https://doi.org/10.1080/21580103.2017.1417920
25. Khan MNI, Islam MR, Rahman A, Azad MS, Mollick AS, Kamruzzaman M, et al. Allometric relationships of stand level carbon stocks to basal area, tree height and wood density of nine tree species in Bangladesh. Glob Ecol Conserv. 2020;22.
26. Alamgir M, Al-Amin M. Organic carbon storage in trees within different Geopositions of Chittagong (South) Forest Division, Bangladesh. J For Res. 2007;18:174–80.
27. Mandal RA, Jha PK, Dutta IC, Thapa U, Karmacharya SB. Carbon Sequestration in Tropical and Subtropical Plant Species in Collaborative and Community Forests of Nepal. Advances in Ecology.2016; http://dx.doi.org/10.1155/2016/1529703
28. Ullah MR, Banik GR, Banik R. Developing allometric models for carbon stock estimation in eighteen year old plantation forests of Bangladesh. Jacobs Journal Microbiologic Pathologists, 2014;1:1–8
29. Day M, Baldauf C, Rutishauser E, Sunderland TCH. Relationships between tree species diversity and above-ground biomass in Central African rain forests: implications for REDD. Environ. Conserv. 2013;41:64–72, http://dx.doi.org/10.1017/S0376892913000295
30. Shen Y, Yu S, Lian J, Shen H, Cao H, Lu H, Ye W. Tree aboveground carbon storage correlates with environmental gradients and functional diversity in a tropical forest. Sci. Rep. 2016;6:1–10. https://doi.org/10.1038/srep25304
31. Dondini M, Hastings A, Saiz G, Jones M, Smith P. The potential of Miscanthus to sequester carbon in soils: comparing field measurements in Carlow, Ireland to model predictions. Glob Change Biol

Bioenergy 2009;1:413–425

32. Ostertag R, Marín-Spiotta E, Silver WL, Schulten J. Litterfall and decomposition in relation to soil carbon pools along a secondary forest chronosequence in Puerto Rico. Ecosystems 2008;11:701–714
33. Houghton RA. Balancing the global carbon budget. Annu Rev Earth Planet Sci. 2007;35:313–347
34. Ullah MR, Al-Amin M. Above- and below-ground carbon stock estimation in a natural forest of Bangladesh. J For Sci. 2012;58:372–9.
35. Danquah JA, Appiah M, Pappinen A. Effect of African mahogany species on soil chemical properties in degraded dry semi-deciduous forest ecosystems in Ghana. Int J Agric Biol. 2012;14:321–8.
36. Sayer EJ, Lopez-Sangil L, Crawford JA, Bréchet LM, Birkett AJ, Baxendale C, et al. Tropical forest soil carbon stocks do not increase despite 15 years of doubled litter inputs. Sci Rep. 2019;9:1–9.
37. Miao R, Ma J, Liu Y, Liu Y, Yang Z, Guo M. Variability of Aboveground Litter Inputs Alters Soil Carbon and Nitrogen in a Coniferous–Broadleaf Mixed Forest of Central China. Forests 2019;10:(188). doi:10.3390/f10020188
38. Krishna MP, Mohan M. Litter decomposition in forest ecosystems: a review. Energy, Ecol Environ. Joint Center on Global Change and Earth System Science of the University of Maryland and Beijing Normal University; 2017;2:236–49.
39. Akhtaruzzaman M, Osman KT, Sirajul Haque SM. Soil Properties in Two Forest Sites in Cox's Bazar, Bangladesh. J For Environ Sci. 2015;31:280–7.
40. Zaman MA, Osman KT, Sirajul Haque SM. Comparative study of some soil properties in forested and deforested areas in Cox's Bazar and Rangamati Districts, Bangladesh. J For Res. 2010;21:319–22.
41. Barua SK, Haque SMS. Soil Characteristics And Carbon Sequestration Potentials Of Vegetation In Degraded Hills Of Chittagong, Bangladesh. L Degrad Dev. 2013;24:63–71.
42. Kibria MG, Saha N. Analysis of existing agroforestry practices in Madhupur Sal forest: an assessment based on ecological and economic perspectives. J. For. Res. 2011;22:533-542
43. Chen S, Wang W, Xu W, Wang Y, Wan H, Chen D, et al. Plant diversity enhances productivity and soil carbon storage. Proc Natl Acad Sci U S A. 2018;115:4027–32.
44. Isaac SR, Nair MA. Biodegradation of leaf litter in the warm humid tropics of Kerala, India. Soil Biol Biochem. 2005;37:1656–64.
45. Nair PKR, Nair VD, Kumar BM, Haile SG. Soil carbon sequestration in tropical agroforestry systems: a feasibility appraisal. Environ Sci Policy. 2009;12:1099–111.
46. Saha SK, Nair PKR Nair VD, Kumar BM. Soil carbon stock in relation to plant diversity of homegardens in Kerala, India. Agrofor. Syst. 2009;76:53–65, http://dx.doi.org/10.1007/s10457-009-9228-8
47. Lal R. Forest soils and carbon sequestration. For Ecol Manage. 2005;220:242–58.
48. Lal R. Soil carbon stocks under present and future climate with specific reference to European ecoregions. Nutr Cycl Agroecosystems. 2008;81:113–27.

49. Nair PKR, Kumar BM, Nair VD. Agroforestry as a strategy for carbon sequestration. J Plant Nutr Soil Sci. 2009;172:10–23.
50. Homann PS, Bormann BT, Boyle JR, Darbyshire RL, Bigley R. Soil C and N minimum detectable changes and treatment differences in a multi-treatment forest experiment. For. Ecol. Manag. 2008;255:1724–1734
51. Casals P, Romero J, Rusch GM, Ibrahim M. Soil organic C and nutrient contents under trees with different functional characteristics in seasonally dry tropical silvopastures. Plant Soil. 2014;374:643–59.
52. Islam M, Dey A, Rahman M. Effect of Tree Diversity on Soil Organic Carbon Content in the Homegarden Agroforestry System of North-Eastern Bangladesh. Small-scale For. 2015;14:91–101.
53. Gardner TA, Burgess ND, Aguilar-Amuchastegui N, Barlow J, Berenguer E, Clements T, et al., A framework for integrating biodiversity concerns into national REDD+ programmes. Biol. Conserv.2012;154:61–71
54. Takimoto A, Nair PKR, Nair VD. Carbon stock and sequestration potential of traditional and improved agroforestry systems in the West African Sahel. Agric. Ecosyst. Environ. 2008;125:159–166. https://doi.org/10.1016/j.agee.2007.12.010
55. Chave J, Réjou-Méchain M, Búrquez A, Chidumayo E, Colgan MS, Delitti WBC, et al. Improved allometric models to estimate the aboveground biomass of tropical trees. Glob Chang Biol. 2014;20:3177–90.
56. Nair PKR. Carbon sequestration studies in agroforestry systems: a reality check. Agrofor. Syst. 2012;86(2):243–253
57. Jashimuddin M, Inoue M. Management of village common forests in the Chittagong hill tracts of Bangladesh: historical background and current issues in terms of sustainability. Open J. For.2012;2 (3):121–137
58. Majlis AB, Islam M, Khasru MA, Ahsan MK. Protectred to open basin depositional system: An Appraisal for the Quaternary Evolution of the Moheshkhali-Kutubdia Coastal Plain, Bangladesh, Abstract volume. National seminar on Bangladesh Coast: Geology, Hazards and Resources. Dhaka, Bangladesh. 2011
59. Islam MA, Maitra MK, Baquee A, Majlis K, Murshed S, Rahman S. Spatial Changes of Land Use / Land Cover of Moheshkhali Island , Bangladesh : A Fact Finding Approach by Remote Sensing Analysis. Dhaka University Journal of Earth and Environmental Sciences 2012;2:43-54.
60. Upazila Parishad office. Maheshkhali Upazila, Cox´s Bazar District: Bangladesh; 2019
61. District office, Cox´s Bazar District, Chittagong Division: Bangladesh; 2019
62. Banglapedia. 2020. http://en.banglapedia.org/index.php?title=Maheshkhali_Upazila. Accessed 28 Mar 2020
63. Islam MA, Majlis ABK, Bazlar R. Changing face of Bangladesh Coast. Abstract volume. National seminar on Bangladesh Coast: Geology, Hazards and Resources. Dhaka, Bangladesh; 2011.

64. 6 Papry RI. Status of Coastal Plantation in Chittagong Coastal Forest Division. IOSR J Environ Sci Toxicol Food Technol. 2014;8:79–83.
65. DoE (Department of Environment). GIS and Cartographic Services – Final Report, Pre-Investment Facility Study: Coastal and Wetland Biodiversity Management Project (Project BGD/94/G41). Dhaka, Bangladesh;1999
66. Maheshkhali Forest Range Office. Chittagong Coastal Forest Division, Chittagong, Bangladesh Forest Department: Bangladesh; 2019.
67. Union Parishad Office. Bara Maheshkhali, Chatto Maheshkhali, Gorokghata Unions, Cox´s Bazar District, Chittagong Division: Bangladesh; 2019.
68. UN (United Nations). Designing household survey samples: practical guidelines. Publication No. ST/ESA/STAT/SER.F/98. Department of Economic and Social Affairs, Statistics Division: New York; 2005
69. Ensslin A, Rutten G, Pommer U, Zimmermann R, Hemp A, Fischer M. Effects of elevation and land use on the biomass of trees, shrubs and herbs at Mount Kilimanjaro. Ecosphere. 2015;6.
70. Blake GR. 1965. Bulk density. In: Black CA, Evans DD, White JL, Ensminger IE, Clark FE, editors. Methods of Soil Analysis. Part 1. American Society of Agronomy, Wisconsin, USA: Inc. Publisher, Madison; p. 894-895
71. Hairiah K. Measuring carbon stocks: Across land use systems: a manual. Published in close cooperation with Brawijaya University and ICALRRD (Indonesian Center for Agricultural Land Resources Research and Development); 2011
72. Frangi JL, Lugo AE. Ecosystem dynamics of a subtropical floodplain forest. Ecol Monogr. 1985;55(3):351–369
73. Issa S, Dahy B, Ksiksi T, Saleous N. Development of a new allometric equation correlated wth variables for the assessment of date palm biomass. Conference paper. UAE University, College of Science: United Arab Emirates; 2018
74. MacDicken KG. A Guide to Monitoring Carbon Storage in Forestry and Agro-forestry Projects. Arlington, USA: Winrock International; 1997
75. Brown S. 1997. Estimating biomass and biomass change of tropical forests: a primer. FAO Forestry Paper 134. Rome: FAO; 1997
76. Sattar MA, Bhattacharje DK, Kabir MF. Physical and mechanical properties and uses of timbers of Bangladesh. Chittagong, Bangladesh: Bangladesh Forest Research Institute; 1999
77. Chave J, Coomes D, Jansen S, Lewis SL, Swenson NG, Zanne AE. Towards a worldwide wood economics spectrum. Ecol. Lett. 2009;12(4):351–366
78. Zanne AE, Lopez-Gonzalez G, Coomes DA, Ilic J, Jansen S, Lewis SL, et al. Data from: towards a worldwide wood economics spectrum, Dryad Digital Repository. Global Wood Density Database. 2009. http://dx.doi.org/10.5061/dryad.234. Accessed 15 Mar 2020
79. 79. Shukla RS, Chandel PS. Plant ecology and soil science, 9th ed. New Delhi, India: 2000

80. Ball DF. Loss-on-ignition as an estimate of organic matter and organic carbon in noncalcareous soils. J. Soil Sci. 1964;15:84–92. https://doi.org/10.1111/j.1365-2389.1964.tb00247.x
81. Reganold JP, Harsh JB. Expressing cation exchange capacity in milliequivalents 1per 100 grams and in SI units. J. Agric. Educ. 1985;14:(2)
82. Davidson DA. Soil physical measurement and interpretation for land evaluation. Aclep, Land Evaluation Program, 2, 1–16. 1986. https://doi.org/10.4135/9781446216187.n164. Acessed 25 Mar 2020
83. Morais VA. Modelagem, e espacialização do estoque de carbono de cerrado sensu stricto em Minas Gerais. Universidade Federal de Lavras: M.S. thesis; 2012
84. Pearson TRH, Brown SL, Birdsey RA. Measurement Guidelines for the Sequestration of Forest Carbon. General Technical Report NRS-18. USDA FOREST SERVICE, United States Department of Agriculture; 2007
85. Margalef R. Information theory in ecology. General Syst. 1958;3:36–71
86. Michael P. Ecological methods for field and laboratory investigation. New Delhi, India: Tata Mc Graw Hill; 1990
87. Dallmeier F, Kabel M, Rice R. Methods for long-term biodiversity inventory plots in protected tropical forests. In: Dallmeier F, editor. Long-term monitoring of biological diversity in tropical forest areas: Methods for establishment and inventory of permanent plots. Paris, France: UNESCO; 1992. p. 11–46.
88. 88. Poorter L, van der Sande MT, Thompson J, Arets EJMM, Alarcón A, Álvarez-Sánchez J, et al. Diversity enhances carbon storage in tropical forests. Glob Ecol Biogeogr. 2015;24:1314–28.
89. 89. Rahman MM, Kabir ME, Jahir Uddin Akon ASM, Ando K. High carbon stocks in roadside plantations under participatory management in Bangladesh. Glob Ecol Conserv. Elsevier B.V.; 2015;3:412–23.
90. Ordóñez JAB, de Jong BHJ, Garcia-Oliva F, Avina FL, Perez JV, Guerrero G, et al. Carbon content in vegetation, litter, and soil under 10 different land-use and land-cover classes in the Central Highlands of Michoacan, Mexico. For Ecol Manage. 2008;255:2074–2084
91. 91. Baul TK, Datta D, Alam A. A comparative study on household level energy consumption and related emissions from renewable (biomass) and non-renewable energy sources in Bangladesh. Energ. Pol. 2018;114:598–608
92. Hossen MM, Rahman AHMS, Kabir AS, Hasan MMF, Ahmed S. Systematic assessment of the availability and utilization potential of biomass in Bangladesh. Renew. Sustain. Energy Rev. 2017;67:94–105. http://dx.doi.org/10.1016/j.rser.2016.09.008
93. Schleuß P-M, Heitkamp F, Leuschner C, Fender A-C, Jungkunst HF. Higher subsoil carbon storage in species-rich than species-poor temperateforests. Environ. Res. Lett. 2014;9:1–10, http://dx.doi.org/10.1088/1748-9326/9/1/014007
94. Islam KR, Weil RR. Land use effects on soil quality in a tropical forest ecosystem of Bangladesh. Agric Ecosyst Environ. 2000;79:9–16.

95. Jamaludheen V, Kumar BM. Litter of multipurpose trees in Kerala, India: Variations in the amount, quality, decay rates and release of nutrients. For Ecol Manage. 1999;115:1–11.

96. Tubiello FN, Cóndor-Golec RD, Salvatore M, Piersante A, Federici S, Ferrara A, Rossi, S, et al. Estimating Greenhouse Gas Emissions In Agriculture, A Manual to Address Data Requirements for Developing Countries. Rome: Food and Agriculture Organization; 2015

97. Mehling MA, Metcalf GE, Stavins RN. Linking climate policies to advance global mitigation. Science 2018;359: 997–998

Tables

Table 1 Equations used in analyses of data

No	Equation	Reference
1	$AGB\ (kg) = 0.0673 \times (\rho D^2\ H)^{0.976}$, where AGB (kg), ρ wood density (g cm^{-3}), D and H are tree DBH (cm) and height (m), respectively	[55]
2	AGB (kg) = $4.5 + (7.7 \times H)$	[71]
3	AGB (kg) = $10 + 6.4\ H$	[72]
4	AGB (kg) = $-3.956 \times H^2 + (55.247 \times H) - 2.0342$	[73]
5	Stand density, D (individual ha^{-1}) = $\frac{n}{A}$, where, A is an area of the homestead forest (ha)	[79]
6	BA (m^2 $tree^{-1}$) = $3.14 \times (D/2)^2$	[79]
7	LOI % = $W_1/W_2 \times 100$, where, W_1 is loss in weight, W_2 weight of oven dry soil, and LOI is loss of ignition	[80]
8	SOC % = $0.47 \times$ (% LOI – 1.87), where SOC denotes soil organic carbon	[80]
9	Soil C stock (Mg ha^{-1}) = $C_{conc} \times BD \times V$, where, C_{conc} is the concentration of C (kg kg $soil^{-1}$), V volume of soil (m^3), and BD bulk density (kg m^{-3})	[81]
10	$Dry\ mass\ of\ the\ litter\ sample\ (DM, g) = \frac{Dry\ mass\ of\ subsample}{Fresh\ mass\ of\ subsample} \times\ Fresh\ mass\ of\ the\ sample$	
11	$Litter\ DM\ in\ subplot\ (Mg\ ha^{-1}) = \frac{DM1+DM2+DM3+DM4+DM5}{5\ or\ number\ of\ DM} \times 10000\ m^2$	[84]
12	$Margalef\ Index = \frac{(N-1)}{\ln(n)}$, where, N is the total number of species and n is the total number of individuals of all species	[85]
13	Shannon-Wiener index, $H = \sum \mathrm{piln}(pi)$, where, pi is the ratio of S to n in a homestead forest.	[86]
14	Frequency (F) $= \frac{Number\ of\ homestead\ forests\ in\ which\ particular\ species\ occurs}{Total\ number\ of\ homestead\ forests\ studied}$	[79]
15	Relative frequency, RF (%) $= \frac{\mathrm{Fi}}{\Sigma \mathrm{Fi}} \times 100$	[87]
16	$Relative\ density, RD\ (\%) = \frac{Total\ number\ of\ individuals\ of\ that\ species\ in\ a\ site}{Total\ number\ of\ individuals\ of\ all\ species\ in\ a\ site}$	[87]

Table2 Mean values of tree DBH, height, species diversity and richness indices in the homestead forests. Different letters within a row indicate significant differences at $p \leq 0.05$.

Variables/site categories	Hillside	Beachside	Inland	Total mean
Mean DBH (cm)	22.87 ± 0.70 ^{a}	14.64 ± 1.43 ^{c}	18.98 ± 0.86 ^{b}	18.82 ± 0.62
Mean height (m)	7.86 ± 0.22 ^{a}	4.91 ± 0.47 ^{c}	6.30 ± 0.28 ^{b}	6.34 ± 0.20
Shannon−Weiner diversity index	1.44 ± 0.04 ^{a}	0.96 ± 0.10 ^{b}	1.29 ± 0.06 ^{a}	1.23 ± 0.04
Margalef richness index	1.61 ± 0.06 ^{a}	1.11 ± 0.12 ^{b}	1.27 ± 0.07 ^{a}	1.32 ± 0.05

Table 3Relative frequency (RF, %) and relative density (RD, %)of species found in the homestead forests

No	Species	RF (%)			RD (%)		
		Hillside	Beachside	Inland	Hillside	Beachside	Inland
1	*Acacia auriculiformis*	11.78	9.62	11.76	14.17	14.26	15.03
2	*Acacia mangium*	7.29	3.83	5.74	7.88	5.44	7.11
3	*Aegle marmelos*	0.30	0.43	0.00	0.24	0.19	0.00
4	*Albizia procera*	0.61	2.98	1.99	0.48	1.94	1.54
5	*Anacardium occidentale*	0.91	0.85	0.88	0.48	0.58	0.47
6	*Annona squamosa*	0.30	0.00	0.22	0.12	0.00	0.13
7	*Areca catechu*	4.56	2.55	3.31	9.07	5.24	6.24
8	*Artocarpus heterophyllus*	8.81	6.38	7.51	8.95	6.41	6.85
9	*Averrhoa bilimbi*	1.22	0.43	0.66	0.48	0.39	0.27
10	*Averrhoa carambola*	0.61	0.00	0.44	0.48	0.00	0.20
11	*Azadirachta indica*	0.00	0.43	0.22	0.00	0.39	0.20
12	*Bombax ceiba*	0.61	0.00	0.44	0.24	0.00	0.13
13	*Chukrasia tabularis*	0.61	0.00	0.66	0.60	0.00	0.27
14	*Citrus maxima*	0.91	0.85	1.32	0.36	0.58	0.74
15	*Clerodendrum viscosum*	0.30	0.43	0.22	0.12	0.19	0.13
16	*Cocos nucifera*	11.18	17.31	11.33	15.37	12.86	15.96
17	*Dellenia indica*	0.00	0.85	0.44	0.00	0.58	0.27
18	*Diospyros blancoi*	0.00	1.28	0.44	0.00	0.58	0.27
19	*Diptercarpus turbinatus*	0.91	4.26	2.43	0.36	2.33	1.54
20	*Elaeocarpus floribundus*	0.00	0.85	0.44	0.00	0.58	0.20
21	*Erythrina orientalis*	0.30	0.43	0.22	0.12	0.19	0.07
22	*Eucalyptus sp*	0.30	0.85	0.44	0.24	0.97	0.40
23	*Ficus racemosa*	0.30	0.85	0.44	0.12	0.39	0.20
24	*Garcinia cowa*	0.00	0.43	0.22	0.00	0.19	0.07
25	*Gemlina arborea*	0.91	4.26	1.99	0.48	3.50	1.81
26	*Hevea brasiliensis*	0.91	0.43	0.88	0.36	0.58	0.47
27	*Hopea odorata*	0.61	1.28	1.10	0.36	0.97	0.67

No	Species	RF (%)			RD (%)		
		Hillside	Beachside	Inland	Hillside	Beachside	Inland
28	*Lagerstroemia speciosa*	0.00	0.00	0.44	0.00	0.00	0.20
29	*Lannea coromandelica*	0.91	1.28	1.77	0.36	0.78	1.54
30	*Lichi chinensis*	1.22	0.85	1.32	0.60	0.97	0.81
31	*Magnolia champaca*	0.61	0.00	0.22	0.24	0.00	0.07
32	*Mangifera indica*	14.59	11.06	13.02	20.41	14.76	14.16
33	*Manilkara zapota*	0.30	0.43	0.66	0.12	0.39	0.34
34	*Mimusops elengi*	0.00	0.43	0.22	0.00	0.39	0.13
35	*Moringa oleifera*	0.30	0.43	0.00	0.12	0.19	0.00
36	*Neolamarckia cadamba*	0.30	0.43	0.22	0.12	0.39	0.27
37	*Phoenix dactylifera*	0.61	0.00	0.44	0.24	0.00	0.27
38	*Phyllanthus emblica*	0.00	0.43	0.22	0.00	0.19	0.20
39	*Polyalthia longifolia*	0.30	0.00	0.44	0.12	0.00	0.20
40	*Psidium guajava*	4.56	5.11	3.97	4.06	3.88	3.56
41	*Pterygota alata*	0.61	0.43	0.44	0.24	0.19	0.34
42	*Samanea saman*	6.08	8.09	7.06	4.53	5.24	5.84
43	*Spondias pinnata*	0.61	0.85	0.22	0.24	0.78	0.07
44	*Swietenia mahagoni*	5.17	7.66	5.96	4.65	7.96	5.44
45	*Syzygium samarangense*	0.00	0.43	0.00	0.00	0.19	0.00
46	*Syzygium sp*	3.65	2.13	2.87	1.91	1.36	2.08
47	*Tamarindus indica*	0.00	0.43	0.44	0.00	0.19	0.34
48	*Terminalia arjuna*	0.61	0.43	0.44	0.24	0.19	0.40
49	*Terminalia catappa*	0.00	0.00	0.44	0.00	0.00	0.27
50	*Trewia nudiflora*	0.61	0.00	0.00	0.36	0.00	0.00
51	*Vitex peduncularis*	0.61	0.85	0.88	0.24	0.58	0.94
52	*Ziziphus mauritiana*	4.56	4.26	3.53	2.86	2.91	1.95

Table 4 Soil carbon (C) concentration and bulk density (BD) at three different depths in homestead forests.

Site categories	Soil depth (cm)	BD (g cm^{-3})	C concentration (mg g^{-1})
Hillside	10	1.3	16.33
	20	1.31	5.85
	30	1.35	3.00
Beachside	10	1.3	15.14
	20	1.38	6.81
	30	1.4	2.76
Inland	10	1.31	14.90
	20	1.32	6.09
	30	1.36	3.71

Figures

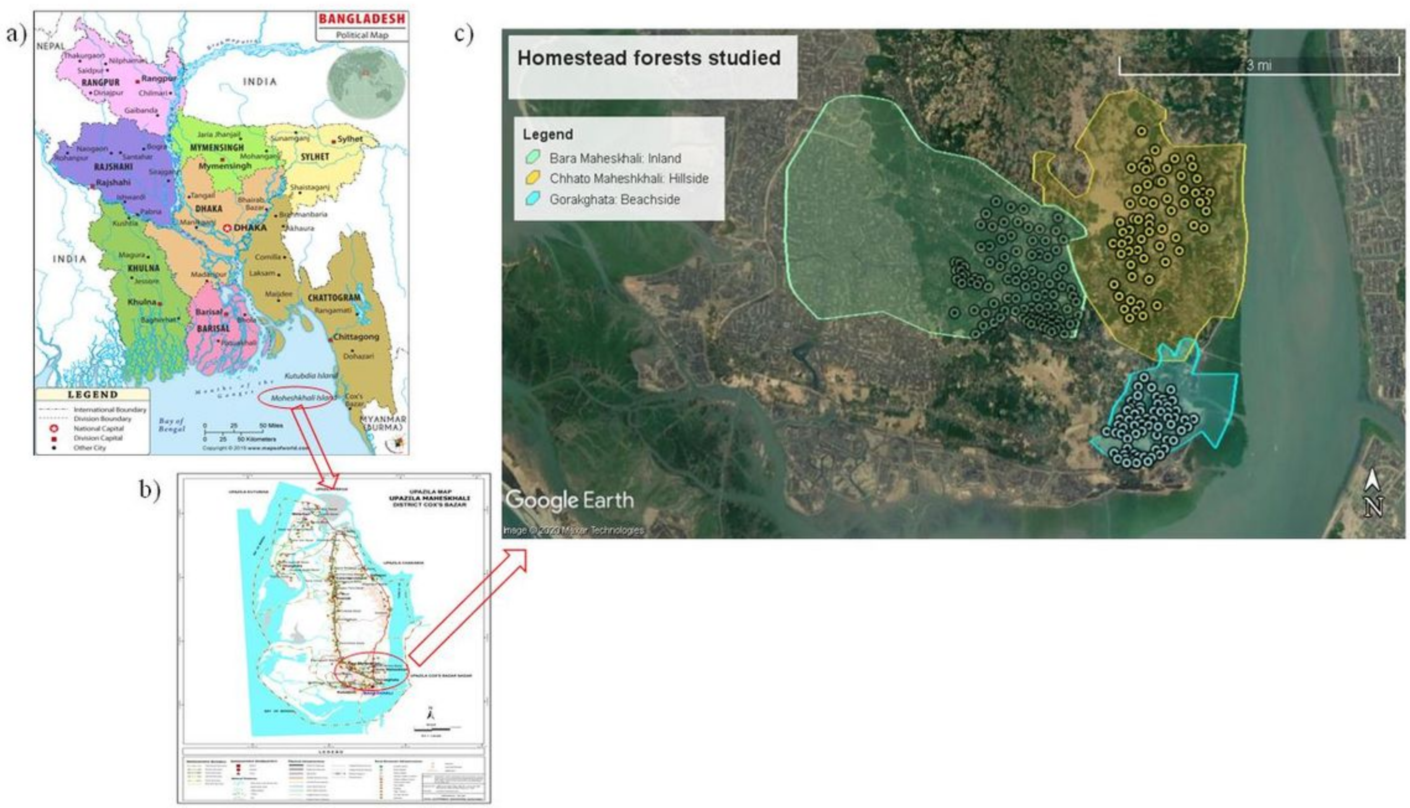

Figure 1

Map of a) Bangladesh and b) Maheshkhali Island showing three categorized study sites with c) sampling points of homestead forests.

a) b)

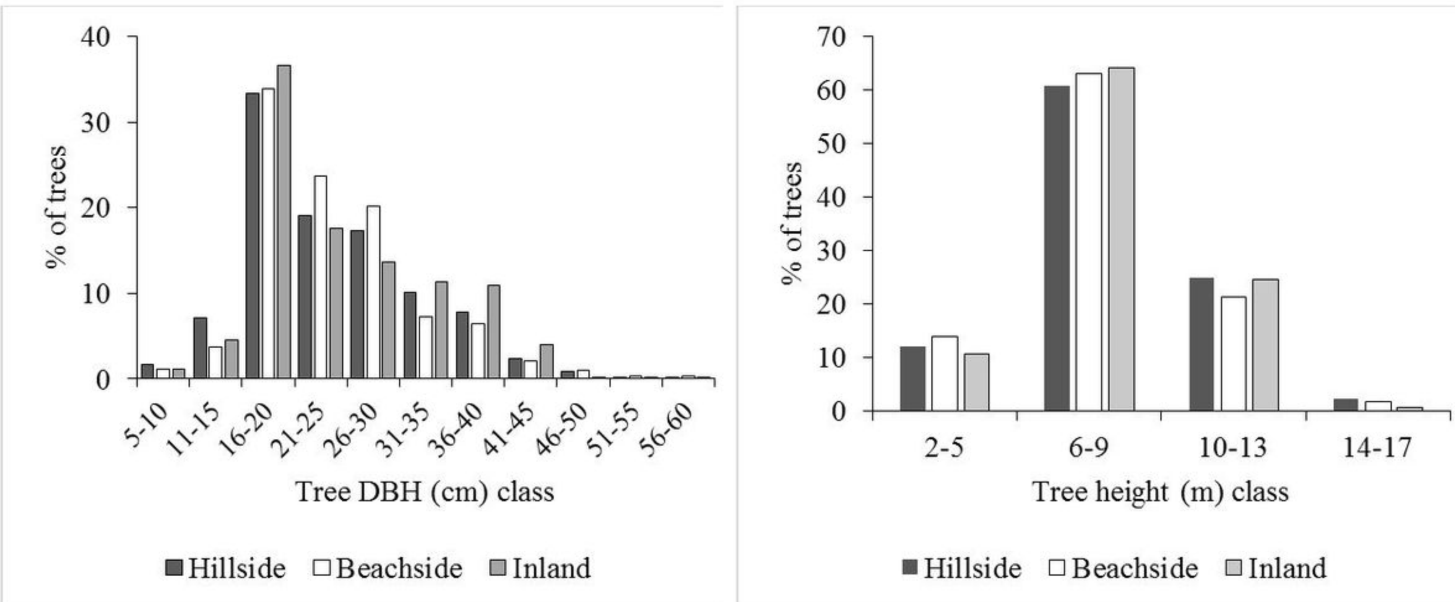

Figure 2

Tree a) DBH (cm) and b) height (m) classes in homestead forests

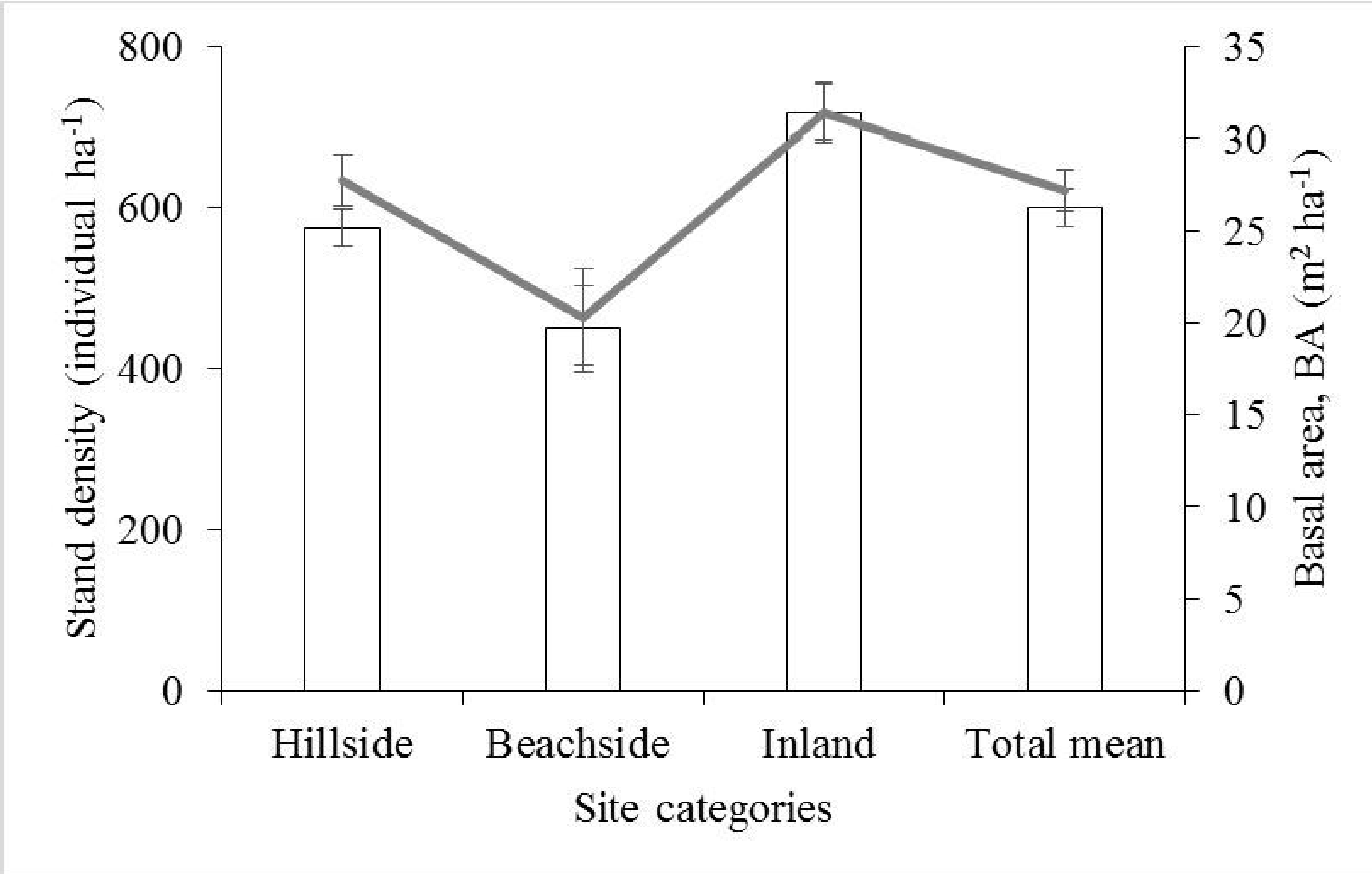

Figure 3

Stand density (primary y axis) and basal area (secondary y axis) in the homestead forests. Bars represent standard error of mean.

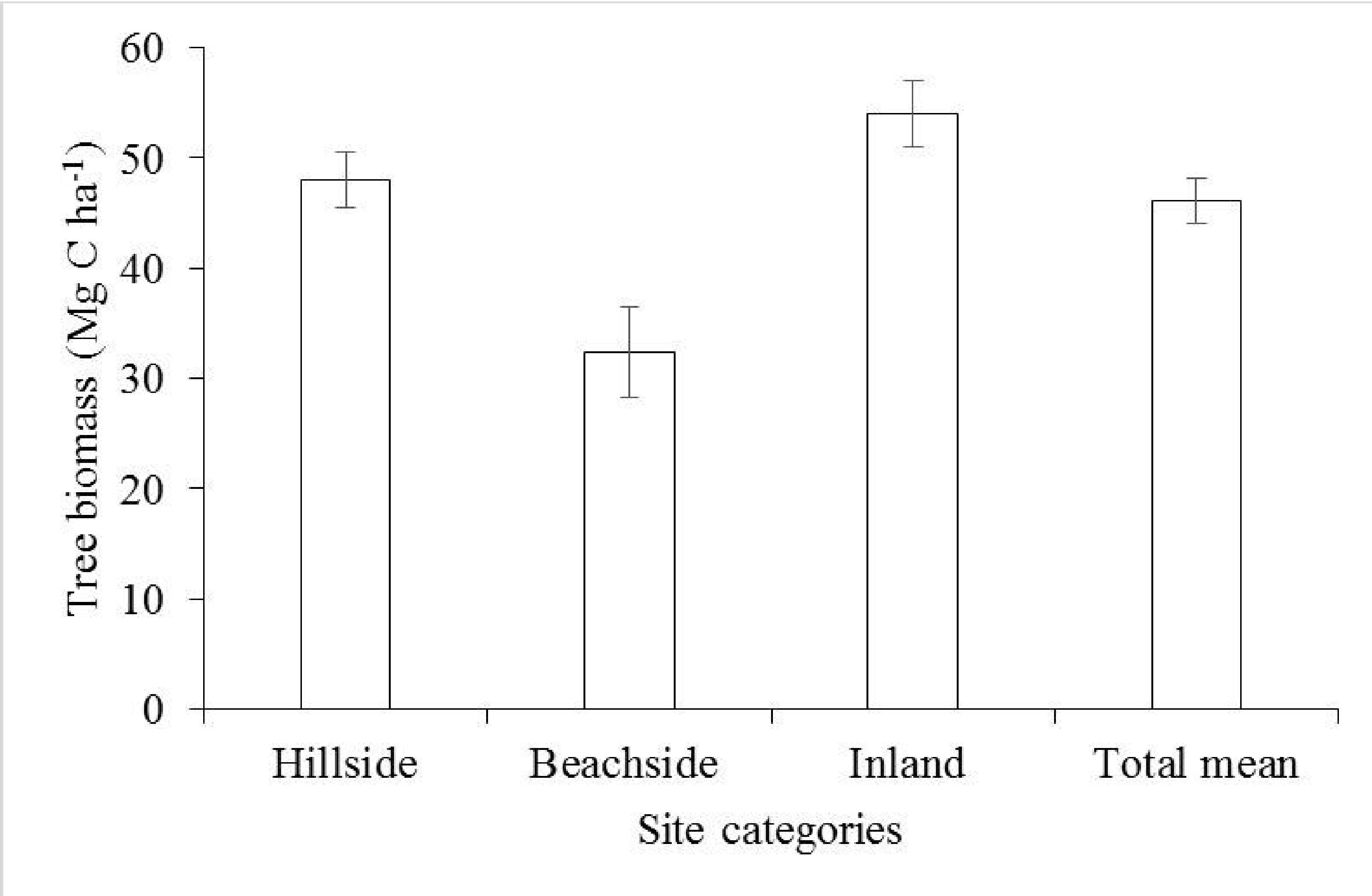

Figure 4

Tree (above-and below-ground) biomass in the homestead forests. Bars represent standard error of mean.

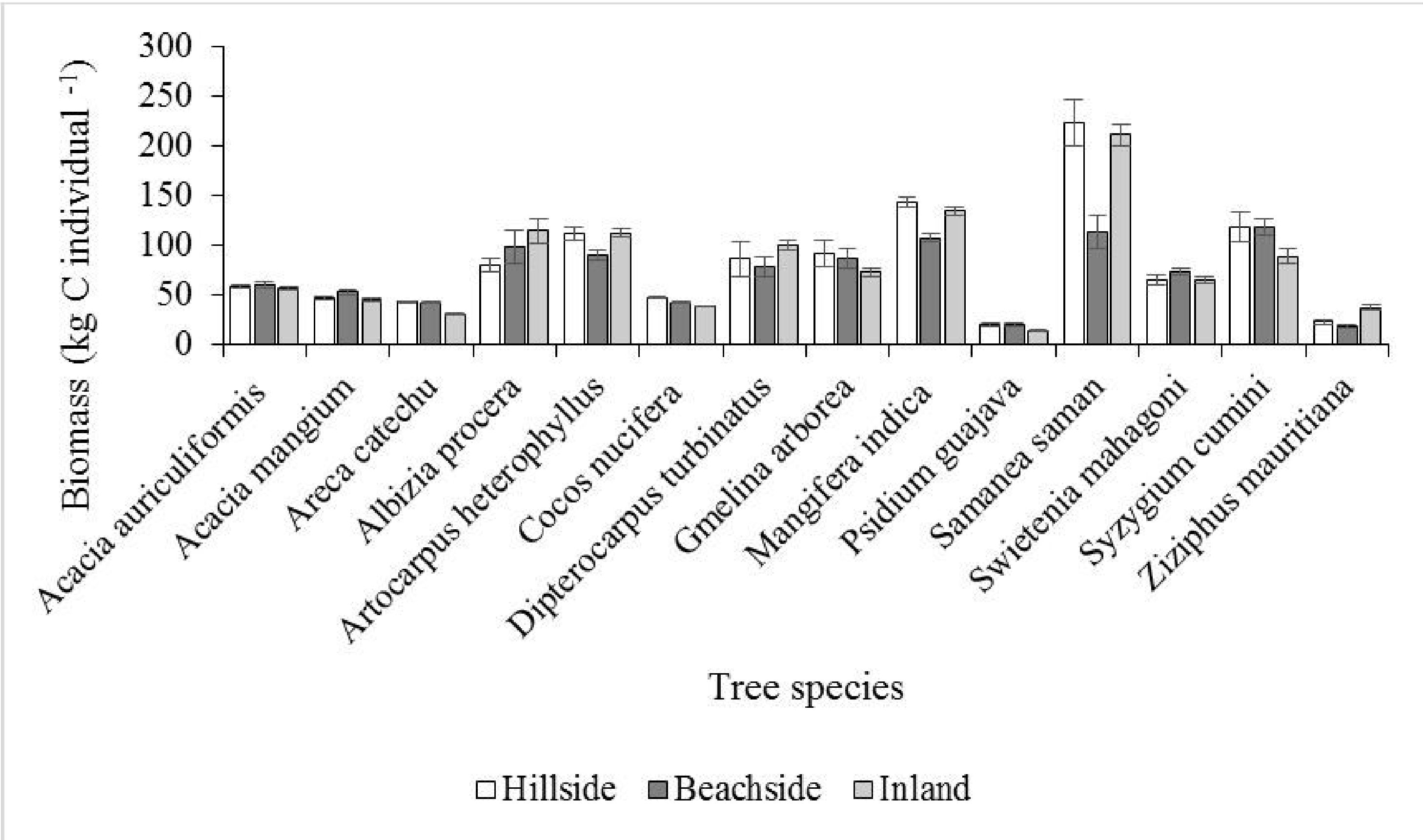

Figure 5

Tree (above-and below-ground) biomass for most frequent species in the homestead forests. Bars represent standard error of mean.

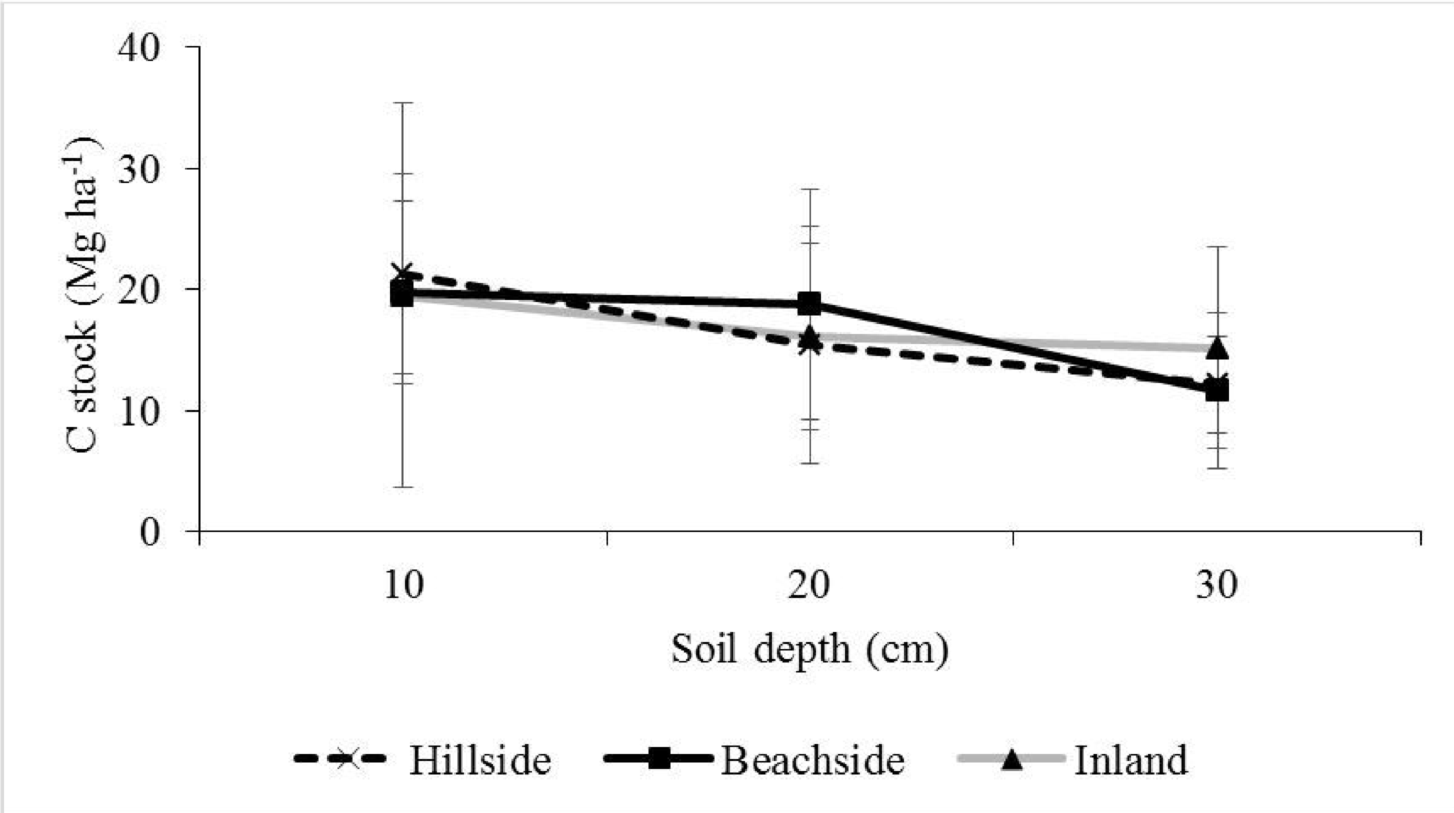

Figure 6

Carbon stocks in mineral soil at three different depths in homestead forests. Bars represent standard error of mean.

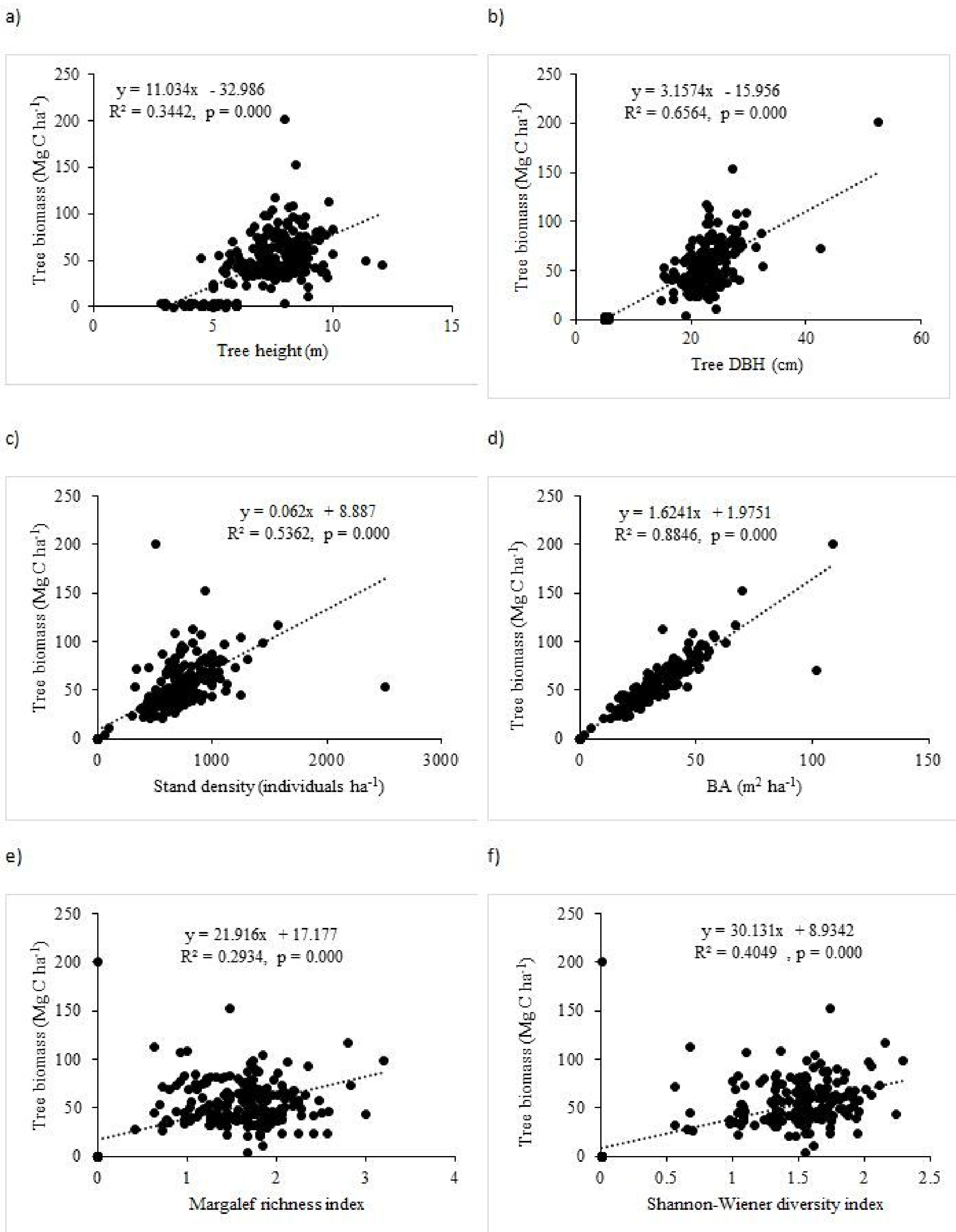

Figure 7

Relationship between tree biomass and a) height, b) DBH, c) stand density, d) basal area, e) Margalef index, and f) Shannon-Wiener index in the homestead forests