

Estimating carbon stocks and woody perennials diversity in cropland agroforestry practiced at three different land ecosystems in Bangladesh

Mohammad Kamrul Hasan

mkhasanaf@bau.edu.bd

Bangladesh Agricultural University

Nasima Akther Roshni

Bangladesh Agricultural University

Rojina Akter

Bangladesh Agricultural University

Research Article

Keywords: Species richness, Diversity indices, Carbon stocks, Agroforestry systems, Soil organic carbon

Posted Date: January 25th, 2024

DOI: <https://doi.org/10.21203/rs.3.rs-3890555/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License. [Read Full License](#)

Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Carbon Balance and Management on February 17th, 2025. See the published version at <https://doi.org/10.1186/s13021-024-00288-8>.

Abstract

Background

Cropland agroforestry practices are widely adopted over various land ecosystems in Bangladesh, offering the potential to capture carbon (C) and safeguard biodiversity. Lack of accurate assessments of biomass carbon and the diversity of woody perennials in cropland agroforestry practices across different land ecosystems presents a hurdle for the efficient execution of initiatives such as REDD + and comparable mechanisms. The present research sought to estimate biomass carbon stocks and diversity of woody species, exploring the influence of stand structure and diversity indices on these C stocks. We conducted woody perennials' inventory in 180 sampling quadrates (10 m × 10 m) from cropland agroforestry practices in forest, plain land, and char land ecosystems.

Results

Altogether, we identified 42 woody species; however, the predominant species in three land ecosystems were *Acacia auriculiformis*, *Gmelina arborea*, and *Tectona grandis*. *Swietenia macrophylla* and *Swietenia mahogany* contributed the greatest amount of carbon stocks. Carbon stocks in woody perennials were 30–44% higher in plainland and forest land ecosystems compared to the char land ecosystem, attributable to significantly increased stand density, basal area, and diameter. The significantly highest Shannon-Wiener index (2.75) and Margalef's richness index (3.37) were found in forest land compared to other ecosystems. The highest total carbon stocks (131.27 Mg C ha⁻¹) of cropland agroforestry were found in the forest land ecosystem, which had the greatest soil organic carbon, density, and richness of woody perennials. A rise in the richness and diversity index of woody species by one unit led to a concurrent increase of 12 and 8 Mg C ha⁻¹ in carbon stock, respectively.

Conclusions

Cropland agroforestry practices in the forest land ecosystem are more diverse and could sequester more carbon stock than in the other two land ecosystems in Bangladesh. The biomass C stocks of woody species were positively correlated with stand structure and diversity, having the potential to contribute to biodiversity conservation in Bangladesh and other similar countries.

Introduction

The gradual elevation in global carbon dioxide (CO₂) emissions and subsequent temperature increments has emerged as a noteworthy issue in the effort to lessen emissions (UNFCCC, 2015; IPCC, 2018). The continuous release of atmospheric CO₂ that is responsible for climate change is caused by human activity, including significant modifications in land use, deforestation, and the burning of petroleum and natural gas (Nawaz et al., 2017; Yasin et al., 2021). CO₂, a predominant greenhouse gas, stands as the primary contributor, exceeding 70%, to the warming of the planet, with its concentration experiencing a sharp upswing since the industrial era (Gupta et al., 2019). The annual uptick in atmospheric CO₂ hovers around 3.5 ppm, presenting substantial hazards to the worldwide environment (Alemu, 2014). If this trajectory persists into the next century, it could result in a potential 2°C temperature surge, leading to a 20–30% reduction in ecosystems globally by 2030 (Nawaz et al., 2017; Agevi et al., 2017). Owing to the adverse effects of climate change, Bangladesh is acknowledged as one of the most susceptible nations (Hanif et al., 2014). Despite its minimal contribution to global emissions, Bangladesh encounters a swift escalation in CO₂ emissions over time, exemplified by a 609% increase in 2017 (78 Mt of CO₂) compared to 1990 (11 Mt of CO₂), primarily attributable to heightened energy consumption (Baul et al., 2021; IEA, 2020).

Agroforestry has been recognized as a feasible way for mitigating greenhouse gas (GHG) emissions under Kyoto Protocol frameworks due to its holistic approach (Sarkar et al., 2021; Das et al., 2020; Birhane et al., 2020). According to estimates by the IPCC (2019), agroforestry has the ability to lower greenhouse gas levels by 0.08 to 5.7 metric tonnes of CO₂ annually. Additionally, agroforestry systems also provide opportunities for significant carbon dioxide sequestration, boosting carbon

stocks above and below ground (Noponen et al., 2013; Nair et al., 2009). Globally, there are approximately 1.6 billion hectares of agroforestry systems, with 78% of the land in tropical regions and 22% in temperate zones (Nair et al., 2021). Also, agroforestry practices sequester a significant amount of carbon, ranging from 30 Pg C yr⁻¹ to 322 Pg C yr⁻¹ (Jose and Bardhan, 2012). With improved tree management practices, an additional 12,000 t C yr⁻¹ could be sequestered, potentially increasing to 17,000 t C yr⁻¹ within 2040. The influence of any type of agroforestry practice on soil organic carbon (SOC) and atmospheric carbon sequestration is dependent on various parameters, including the quality and quantity of biomass input, non-woody system components, and soil characteristics (Nair *et al.*, 2009). Agroforestry systems are more effective at sequestering carbon than annual cropping systems (Henry *et al.*, 2009). In Bangladesh, various agroforestry techniques, particularly cropland agroforestry (CAF), are widely adopted to benefit local farmers across diverse land environments. CAF, a traditional land-use practice in Bangladesh, involves the intentional cultivation and management of trees in agricultural areas for domestic needs, commodities, and cash crops (Chakraborty, 2015). Different ecological zones in Bangladesh exhibit distinct vegetation patterns in cropland agroforestry, reflecting both ecological and socio-economic variations (Shams, 2013). Trees are planted along field boundaries or inside the field at regular or irregular intervals with rice, legumes, oilseeds, wheat, sugarcane, jute, and vegetables. Farmers also cultivate shade-tolerant crops like ginger, turmeric, and aroids in areas with high canopy coverage from trees like mahogany and jackfruit (Ghosh et al., 2011).

Cropland agroforestry practices have been developed in the Madhupur area of the Sal forests on both privately owned land and land managed by the forest department. Horticultural and agronomic crops are grown next to fruit and timber trees, giving locals a range of options and chances to increase farm output and income while also protecting and producing an ecosystem (Akter et al., 2022; Kibria and Saha, 2011). Cropland agroforestry in plainland areas is a traditional land-use system in Bangladesh where perennial trees are grown in or around cropland. This is not just the technique of planting trees on the fields; rather, it offers farmers an efficient land management system that may guarantee increased productivity in an ecologically balanced setting (Chakraborty et al., 2015; FAO, 2004). The char land is yet another important location for cropland-based agroforestry activities. The pertinent literature states that in char land parts of Bangladesh, agroforestry practices are typically used to grow a variety of seasonal crops together with fruit and timber trees, including jackfruit, jujube, guava, mango, citrus, mahogany, and others.

Several studies emphasize that a well-designed and effectively managed multi-layered cropping system in cropland agroforestry can significantly improve both agricultural and forestry production in Bangladesh. Although some research has assessed above-ground forest carbon stocks, covering various areas such as mangrove, coastal, protected contiguous and fragmented, hill, and homestead regions in Bangladesh, there is a noticeable lack of quantifiable data and little information related to cropland agroforestry practices. Specifically, there is a paucity of comprehensive understanding regarding the carbon sequestration potentials, diversity of woody species within cropland agroforestry across diverse land ecosystems in Bangladesh. The existing gaps in knowledge and practical implementation in this domain are particularly prominent. Therefore, it is crucial to evaluate and compare cropland agroforestry techniques across Bangladesh's various land ecosystems in terms of composition, diversity and carbon stock potentials of woody perennials. As a result, this research will assist decision-makers and concern authorities in quantifying the potentialities of cropland agroforestry techniques to protect biodiversity and store carbon to mitigate global climate changes.

Methodology

Study sites

Description of cropland agroforestry practices in the study area

Prior to data collection, three preliminary field visits for practical observation were done in March 2022 to obtain comprehensive knowledge about the study area. This included observation of general conditions: location, physiography, forest and char land areas, and the existence of cropland agroforestry and woody perennial planting systems in cropland along the forest, plain, and char land in the study area. In Bangladesh, cropland agroforestry has been practiced for ages in some confined areas as their traditional agricultural system. In cropland agroforestry, farmers grow woody perennials or trees in or

around the cropland. This is not only the practice of growing trees in the fields; rather, it's a method of land management that helps farmers achieve both increased output and ecological balance. Cropland agroforestry practices cause economic benefits to the farmer in a sustainable and environment-friendly way. In the study area, different methods are practiced for woody perennials or tree plantings on cropland, and among these three major methods are identified in most cases, such as scattered plantation, strip plantation, and boundary plantation.

Scattered plantation: Woody perennials are grown on the crop field randomly, maintaining an 8 m spacing at various designs. The farmers sometimes do not follow any spacing or design rules. Consequently, trees are grown in the cropland in an uncontrolled manner.

Strip plantation: Woody perennials are planted on the crop field in strips, and crops are grown there as intercropping in between the strips.

Boundary plantation: Woody perennials are planted on the edge or on the boundaries of the cropland.

Selection of study sites and woody perennial measurements in cropland agroforestry

The research was conducted on cropland agroforestry practices in three land ecosystems, viz., forest land ecosystem, char land ecosystem, and plain land ecosystem were considered as the treatment of the study. The research sites we selected were three forest ranges (Rasulpur, Auronkhola, and Dhukhola) under Madhupur Sal forest, four unions Ramgopalpur and Dhakakhala under Gauripur, and Char Ishwardia and Char Nilakashmia at Sadar Upazila of Mymensingh district to explore biomass carbon stocks, woody perennials, and the diversity of cropland agroforestry practices at three different land ecosystems. We measured a total of 180 sample quadrat plots, of which 60 were in each of three different land ecosystems, following a simple random sampling method (Fig. 2). In the case of scattered and strip plantations in cropland, the size of each quadrat plot was (10 m × 10 m) for mature trees (≥ 5 cm dbh) and (5 m × 5 m) sub-quadrat for shrubs. But in boundary cropland agroforestry, quadrat size was (2 m × 10 m) for tree species and (2 m × 5 m) for shrubs. To estimate biomass carbon stocks, all woody perennial identification, height (m), and girth at breast height (GBH, cm) measurements were done. The landowners assisted in identifying the woody species with their native names, and in some cases, the leaf herbarium was constructed to confirm the identity of species with their botanical names. The height of woody perennials was determined by the Sunnto Clinometer and GBH by measuring tape. Herbs were not considered in the estimation of carbon stock. The cropland agroforestry in three land ecosystems was thought to show a different kind of ecotype. We hypothesised that the carbon stock of cropland agroforestry practices in three different land ecosystems differs from each other, and stand structure as well as diversity affect these C stocks.

Soil sample collection for estimating carbon stock

A total of 360 soil samples were collected at 15 and 30 cm depths of soil in the selected study sites. Using an auger, five soil cores were extracted from each plot at both depths and placed in labelled polythene bags. Composite samples were made by mixing the collected soil cores from a specific plot and carried to the laboratory.

Soil sample analysis and estimation of carbon

To determine the organic carbon of soil (SOC), the composite soil samples were kept on brown paper in the laboratory of the Agroforestry Department to allow them to air dry. After the soils had been dried in the open air, they were crushed with a pestle and mortar and sieved through a 2 mm sieve to get rid of any visible foreign particles, stones, roots, and other debris. Then the soil samples were packed in airtight polybags with specific tag. The soil samples were analyzed in the laboratory of the Regional Station, Soil Resources Development Institute (SRDI), Jamalpur, Bangladesh. The wet oxidation method was used to calculate organic carbon (OC%) (Eq. No. 18), according to Page *et al.* (1989). Carbon stocks of soils (SOC%) at two depths were calculated using Eq. No. 17 for three different land ecosystems (Table 1).

Data analyses

Estimation of basal area, stand density, and biomass carbon stocks of woody perennials

Basal area (BA), stand density, and DBH were estimated using (Eq. No. 1–3) respectively. The allometric equations (Eq. No. 4–6), as shown in Table 1, were used to convert data into biomass for measuring above-ground biomass (AGB) for tropical trees, palms, and fruit tree species (Brown *et al.*, 1997; Chave *et al.*, 2005; Pearson *et al.*, 2005). The below-ground biomass (BGB) was determined by multiplying the AGB by 0.26 (Eq. No. 7) (Hangarge *et al.* 2012). The sum of above and below-ground biomass was used to compute the total biomass (TB) of woody perennials. Recognizing that carbon makes up around 50% of a plant's biomass, the carbon stock of woody perennials was calculated using Eq. No. 9 (Pearson *et al.*, 2005). The data on wood density (g cm^{-3}), was sourced from the Bangladesh Forest Research Institute (BFRI) (Sattar *et al.*, 1999). When this data was not accessible in BFRI publications, wood density for diverse woody species was collected from the global wood density database assembled by Chave *et al.* (2009). Additionally, carbon content at the species level was calculated for the most frequently occurring woody perennials and expressed in $\text{Kg C individual}^{-1}$ across three land ecosystems.

Estimation of the richness, diversity, relative density, relative frequency, and important value index of woody perennials

The species richness and diversity of woody perennials were calculated using the Shannon-Wiener index (H) and Margalef index following Eqs. No. 10 and 11, as outlined in Table 1. Additionally, relative density (RD%), frequency (F%), relative frequency (RF%), relative dominance ($\text{RD}_0\%$), and important value index (IVI%) for each species were determined using Eq. No. 12–16. Mean values for height (m), diameter at breast height (DBH, cm), all diversity indices, relative frequency (RF%), and relative density (RD%), relative dominance ($\text{RD}_0\%$) and important value index (IVI%) were compared across three different land ecosystems.

Statistical analysis

The one-way ANOVA (analysis of variance) in combination with Tukey's post hoc test was utilized to determine if there were statistically significant differences ($p \leq 0.05$) among the three distinct land ecosystems. It aimed to identify which land ecosystem exhibited significant variations from the others in terms of biomass carbon of woody species (Mg C ha^{-1}), height (m), DBH (cm), density ($\text{individual ha}^{-1}$), basal area ($\text{m}^2 \text{ ha}^{-1}$), Margalef's richness index, and Shannon-Wiener diversity index. To explore the relationship between biomass carbon stock (Mg C ha^{-1}) and characteristics of woody perennials—namely, (a) height (m), (b) DBH (cm), (c) density ($\text{individual ha}^{-1}$), (d) basal area ($\text{m}^2 \text{ ha}^{-1}$), (e) Margalef's richness index, and (f) Shannon-Wiener diversity index—linear regression analysis was employed. Furthermore, multiple regression analysis was employed to model the combined impact of all variables (a–f) on the biomass carbon of woody species. Minitab software (version 17) was utilized to perform all types of statistical analyses of the recorded data.

Results

Stand structure, composition and diversity of woody perennials

Among the identified 42 woody perennial species in cropland agroforestry practices, the distribution across the three ecosystems was as follows: 21 species in the forest land ecosystem, 20 in the char land ecosystem, and 26 in the plain land ecosystem (Table 2). The respective counts of sampled woody perennial individuals were 432, 321, and 362 for the forest land, char land, and plain land ecosystems. In the forest land ecosystem, *Acacia auriculiformis* (IVI = 40.81%) emerged as the dominant species, contributing to 15.58% relative density, 13.33% relative frequency, and 11.90% relative dominance. The char land ecosystem was characterized by *Swietenia mahogany* (IVI = 96.05%) as the dominant species, exhibiting 40.31% relative density, 30.48% relative frequency, and 25.26% relative dominance, followed by *Samanea saman* and *Eucalyptus camaldulensis* (Table 2). Meanwhile, the plain land ecosystem was dominated by *Swietenia macrophylla* (IVI = 73.27%), with 27.35% relative density, 20.15% relative frequency, and 25.77% relative dominance, followed by *Swietenia mahogany*, *Areca catechu*, and *Mangifera indica* (Table 2).

Table 2

Relative Density (RD%), Relative Frequency (RF%), Relative Dominance (RD₀) and Important Value Index (IVI) of identified woody perennials of cropland agroforestry practices at three different ecosystems

Name of species	RD (%)			RF (%)			RD ₀ (%)			IVI (%)		
	FLE	CLE	PLE	FLE	CLE	PLE	FLE	CLE	PLE	FLE	CLE	PLE
<i>Acacia spp.</i>	1.86	--	0.28	2.67	--	0.75	3.02	--	0.04	7.55	--	1.07
<i>Aquilaria agallocha</i>	7.91	--	--	5.33	--	--	4.84	--	--	18.08	--	--
<i>Acacia auriculiformis</i>	15.58	6.35	10.50	13.33	8.42	10.45	11.90	8.63	13.35	40.81	23.41	34.29
<i>Phyllanthus emblica</i>	2.09	--	--	1.33	--	--	16.27	--	--	19.70	--	--
<i>Calyptanthus jombolana</i>	0.55	--	--	0.75	--	--	0.50	--	--	1.80	--	--
<i>Terminalia bellirica</i>	1.86	--	--	1.33	--	--	3.12	--	--	6.32	--	--
<i>Swietenia macrophylla</i>	3.95	0.94	27.35	4.00	1.90	20.15	3.88	0.51	25.77	11.83	3.35	73.27
<i>Areca catechu</i>	--	0.94	10.77	--	0.95	8.21	--	0.31	4.39	--	2.20	23.37
<i>Botnaya</i>	--	--	0.28	--	--	0.75	--	--	0.45	--	--	1.47
<i>Artocarpus chaplasi</i>	2.33	--	--	5.33	--	--	3.35	--	--	11.01	--	--
<i>Alstonia scholaris</i>	--	--	0.28	--	--	0.75	--	--	1.54	--	--	2.56
<i>Chukrasia tabularis</i>	2.56	--	--	2.67	--	--	2.40	--	--	7.62	--	--
<i>Swietenia mahogany</i>	--	40.31	11.88	--	30.48	7.46	--	25.26	9.21	--	96.05	28.55
<i>Eucalyptus camaldulensis</i>	--	6.88	--	--	6.67	--	--	11.14	--	--	24.68	--
<i>Gmelina arborea</i>	4.65	1.88	1.66	5.33	2.86	1.49	9.34	0.34	0.93	19.32	5.07	4.08
<i>Dipterocarpus turbinatus</i>	2.33	--	--	2.67	--	--	4.27	--	--	9.26	--	--
<i>Psidium guajava</i>	8.60	--	--	4.00	--	--	3.04	--	--	15.65	--	--
<i>Syzygium cumini</i>	4.65	0.31	5.80	10.67	0.95	2.99	6.44	0.87	3.72	21.76	2.13	12.51
<i>Elaeocarpus serratus</i>	--	3.44	1.66	--	5.71	4.48	--	2.53	3.81	--	11.68	9.95
<i>Anthocephalus chinensis</i>	--	2.81	3.04	--	1.90	5.97	--	3.34	2.90	--	8.05	11.91
<i>Artocarpus heterophyllus</i>	--	--	1.93	--	--	2.99	--	--	0.84	--	--	5.76
<i>Albizia procera</i>	--	1.25	0.28	--	1.90	0.75	--	0.71	0.15	--	3.87	1.17

Name of species	RD (%)			RF (%)			RD ₀ (%)			IVI (%)		
	FLE	CLE	PLE	FLE	CLE	PLE	FLE	CLE	PLE	FLE	CLE	PLE
<i>Carissa carandas</i>	--	1.56	0.28	--	1.90	0.75	--	1.43	0.45	--	4.89	1.47
<i>Haldina cordifolia</i>	0.23	--	--	1.33	--	--	1.22	--	--	2.78	--	--
<i>Careya arborea</i>	0.23	--	--	1.33	--	--	1.72	--	--	3.29	--	--
<i>Khaya anthotheca</i>	--	7.19	2.76	--	8.57	2.24	--	7.68	2.89	--	23.44	7.89
<i>Citrus limon</i>	--	0.63	--	--	0.95	--	--	0.08	--	--	1.66	--
<i>Litchi chinensis</i>	8.60	--	--	9.33	--	--	4.43	--	--	22.37	--	--
<i>Acacia mangium</i>	11.63	5.00	1.93	10.67	5.71	2.99	5.88	2.64	0.53	28.17	13.36	5.45
<i>Mangifera indica</i>	--	--	7.73	--	--	8.96	--	--	7.28	--	--	23.97
<i>Cocos nucifera L.</i>	--	--	2.76	--	--	2.24	--	--	8.71	--	--	13.71
<i>Azadirachta indica</i>	7.44	--	--	5.33	--	--	9.78	--	--	22.55	--	--
<i>Mallotus nudiflorus</i>	--	8.75	--	--	6.67	--	--	5.81	--	--	21.22	--
<i>Aphanamixis polystachya</i>	1.86	--	0.28	1.33	--	0.75	1.98	--	0.10	5.17	--	1.12
<i>Borassus flabellifer</i>	--	2.19	--	--	2.86	--	--	9.93	--	--	14.98	--
<i>Samanea saman</i>	--	7.19	5.25	--	8.57	8.96	--	17.76	8.22	--	33.51	22.43
<i>Shorea robusta</i>	3.02	--	--	4.00	--	--	5.87	--	--	12.90	--	--
<i>Tectona grandis</i>	6.74	--	0.83	6.67	--	1.49	8.16	--	0.79	21.57	--	3.11
<i>Moringa oleifera</i>	--	0.63	--	--	0.95	--	--	0.36	--	--	1.94	--
<i>Dalbergia Sissoo</i>	--	1.25	0.83	--	1.90	0.75	--	1.16	1.12	--	4.32	2.70
<i>Lannea coromandelica</i>	--	--	--	--	--	--	--	--	--	--	--	--
<i>Zizyphus jujuba</i>	--	0.94	0.55	--	0.95	1.49	--	0.55	0.31	--	2.44	2.36

Table 3 showed that the highest mean value of height and DBH of woody perennials was in the forest land ecosystem compared to the char land ecosystem, which showed the lowest values, and these differences were statistically significant ($p \leq 0.05$) among the three land ecosystems (Table 3). The DBH (16–20 cm) class was most abundant, particularly dominating in the plain land ecosystem. Larger woody species with DBH (30–35 cm) were more prevalent in the forest land ecosystem compared to the other two ecosystems (Fig. 2(a)). In terms of height, the majority of woody perennials fell within the (6–11 m)

class, while taller woody species (16–21 m) were more abundant in the forest land and char land ecosystems (Fig. 2 (b)). Table 3 showed that the forest land ecosystem had higher species richness index and diversity of woody species in crop land agroforestry practices ($p \leq 0.05$) than the other land ecosystems. The mean values of stand density and basal area (BA) of cropland-based agroforestry practices were 619 individuals ha^{-1} and 22.61 $\text{m}^2 \text{ha}^{-1}$, respectively. Analyzing the data, the stand density in the forest land ecosystem was significantly higher ($p \leq 0.05$) than in the other two ecosystems, while there was no significant difference between the other two (Fig. 3). The basal area of woody perennials was significantly greater ($p \leq 0.05$) in the forest land and plain land ecosystems compared to the char land ecosystem (Fig. 3).

Table 3

Mean values of different variables of woody species in cropland-based agroforestry across the three land ecosystems.

Variables	Forest land ecosystem	Char land ecosystem	Plainland ecosystem	Total mean
Mean DBH (cm)	20.36 $\pm$ 1.03 ^a	18.33 $\pm$ 1.02 ^a	19.38 $\pm$ 1.00 ^a	19.35 $\pm$ 1.01
Mean height (m)	11.98 $\pm$ 0.54 ^a	9.04 $\pm$ 0.44 ^c	10.43 $\pm$ 0.52 ^b	10.51 $\pm$ 0.50
Shannon–Weiner diversity index	2.75 $\pm$ 0.03 ^a	2.15 $\pm$ 0.04 ^b	2.59 $\pm$ 0.05 ^a	2.49 $\pm$ 0.04
Margalef’s richness index	3.37 $\pm$ 0.35 ^a	2.61 $\pm$ 0.61 ^b	2.16 $\pm$ 0.40 ^b	2.71 $\pm$ 0.45
Note* The different letters within the row indicate significant differences at $p \leq 0.05$ in post hoc (Tukey’s test)				

Total biomass carbon stocks of cropland agroforestry practices at three land ecosystems

The mean value of biomass carbon stocks (AGC and BGC) of woody perennials in cropland agroforestry was 52.75 Mg C ha^{-1} of the study area. The biomass carbon stocks of woody species were greater in the forest land ecosystem compared to char land ecosystem and plain land ecosystem (Table 4). Carbon stocks diminished with increasing depth of soil in cropland agroforestry practices across three land ecosystems. The carbon stocks significantly ($p \leq 0.05$) varied with land ecosystems and soil depths. The greatest carbon stocks were found in the forest land ecosystem at both soil depths. However, the total biomass carbon stocks significantly ($p \leq 0.05$) varied with the land ecosystems (Table 4). The significant greatest total biomass carbon stocks (131.27 Mg C ha^{-1}) were found in the forest land ecosystem, while the lowest biomass carbon stocks (87.76 Mg C ha^{-1}) were found in the char land ecosystem (Table 4). Among the identified woody perennials, *Acacia auriculiformes* dominates in storing biomass carbon in both forest land ecosystems and char land ecosystems, followed by *Gmelina arborea*, *Tectona grandis*. In the plain land ecosystem, *Swietenia macrophylla* sequestered a relatively greater amount of biomass carbon, compared to other ecosystems (Fig. 4).

Table 4
Total biomass carbon stocks (AGC + BGC + SOC) of cropland agroforestry at three different ecosystems.

Type of ecosystems	Biomass carbon of woody perennials			Soil carbon stocks		Total Biomass C (Mg C ha ⁻¹)
	Above ground carbon stocks (AGC) Mg C ha ⁻¹	Below ground carbon stocks (BGC) Mg C ha ⁻¹	Total C stocks of woody species (Mg C ha ⁻¹)	0–15 cm	15–30 cm	
Forest land ecosystem	52.72	13.71	66.43	41.49	23.35	131.27 ^a
Char land ecosystem	34.32	8.92	43.24	25.20	19.32	87.76 ^c
Plain land ecosystem	38.56	10.02	48.58	29.93	20.16	98.67 ^b
Mean	41.86	10.88	52.75	32.21	20.94	105.9

Relationship of biomass carbon stocks with structural compositions of woody perennials in cropland agroforestry practices

Figure 5 showed the significant ($p \leq 0.05$) relationship between biomass carbon stocks (Mg C ha⁻¹) with height (m), DBH (cm), density (individual ha⁻¹), basal area, BA (m² ha⁻¹), Margalef richness index, and Shannon-Wiener diversity index in cropland agroforestry practices across three land ecosystems. The variability in biomass carbon stocks of woody perennials was explained by these factors together through this multiple regression analysis.

Discussion

The present findings show that the greatest number of woody species were found in the 16–20 cm DBH class, which dominated the plain land ecosystem. In comparison to the other two land ecosystems, the forest land ecosystem contained a larger proportion of woody species with a large DBH (30–35 cm). The maximum number of woody perennials were found in the 6–11 m height range. This finding is supported by similar results of Yasin et al., (2021) where they found the diameter (cm) and height (m) of poplar tree species in three distinct planting patterns of agroforestry in semi-arid region of Pakistan (Pattern A: 15.51 ± 2.28 cm, Pattern B: 16.21 ± 1.83 cm, and Pattern C: 15.71 ± 2.46 cm) respectively. According to Hasan *et al.* (2022), Madhupur Sal forest had the most woody species in the DBH (11–15 cm) class range, then the DBH (6–10 cm) class. The plant height and diameter of five-year-old different agroforestry species (*Leucaena leucocephala* (40.10 ft and 7.96 inches), *Melia azedarach* (39.17 ft and 8.43 inches), and *Albizia lebbek* (38.45ft and 7.90 inches)) in Bangladesh were reported by Hanif *et al.* (2015). The diameter class range of the present study indicates that mostly woody species in forest ecosystems have relatively wider diameter classes. In cropland agroforestry practices in forest land ecosystem, crops are cultivated along existing old trees that are grown naturally. In the forest land ecosystem, *Acacia auriculiformis* (IVI = 40.81%) emerged as the dominant species, contributing to 15.58% relative density, 13.33% relative frequency, and 11.90% relative dominance. The char land ecosystem was characterised by *Swietenia mahogany* (IVI = 96.05%) as the dominant species, exhibiting 40.31% relative density, 30.48% relative frequency, and 25.26% relative dominance, followed by *Samanea saman* and *Eucalyptus camaldulensis*. The study by Hasan et al. (2022) found that *Acacia auriculiformis* had the highest relative frequency (32.91%) and the highest IVI (96.86%) in Madhupur Sal forest cropland agroforestry practices. The present study shows that the mean value of biomass carbon stock was 52.75 Mg C ha⁻¹ for woody species, which significantly varied with land ecosystems. The similar type of result that Taluckder *et al.* (2019) mentioned supports this result. In this study, they found that the total highest carbon of the agroforestry system (207.60 t ha⁻¹) was in the barind ecosystem (174.62 t ha⁻¹). However, the present findings compare with other given data on different ecosystems in Bangladesh and other countries. For instance, in Bangladesh, the tree biomass carbon of southern homestead forest (46 Mg C ha⁻¹) was reported by Baul et al. (2021); northern homestead forest (54 Mg C ha⁻¹) Jaman et al. (2016); mangrove forest (99 Mg C ha⁻¹) Mizanur *et al.* (2015) and total forests of Bangladesh (49–121 Mg C

ha⁻¹) Alamgir and Turton (2014). This discrepancy could be clarified by the diminished overall diversity and richness of species observed in our investigation, suggesting a correspondingly lower biomass in comparison with natural forests and homestead. For world context, Saleem et al. (2023) reported that the total biomass of tree species in boundary plantations was 19.3 t ha⁻¹ under the agrisilviculture system in north-western Himalaya, India. Panwar et al. (2022) found the highest above-ground biomass (109.8 Mg ha⁻¹) in block plantations and the lowest (17.14 Mg ha⁻¹) in boundary plantations. Moreover, carbon stocks of various agroforestry systems in different states of India ranged from 31 t C ha⁻¹ to 173.90 t C ha⁻¹ (Yadav et al., 2019; Chauhan et al., 2015; Arora et al., 2014). Tamga *et al.* (2023) found the AGB density of the agroforestry system was around 34.19 Mg ha⁻¹ which was 167% higher than mango plantations, 355% higher than cocoa plantations, and 366% higher than rubber plantations in the Sudanian. However, agroforestry systems' dimensions, site characteristics, species choice, and management techniques all have an impact on how well they function as carbon sinks. In other words, the amount of carbon sequestered by an agroforestry system is contingent upon its specific structure and composition, which can be altered by environmental and socio-economic elements. Furthermore, variations in diameter, stand age, overall stand structure, diversity, and richness within the system contribute to fluctuations in biomass and its associated carbon content in different land ecosystems (Panwar et al., 2022; Bajigo et al., 2015). The greater the richness and diversity, the greater the tree biomass carbon stock. In our study, we found the highest richness and diversity of cropland agroforestry system in the forest land ecosystem in contrast to other land ecosystem. Figure (5e, f) illustrates that increasing species richness and diversity index by one unit resulted in a corresponding increase of 12 and 8 Mg C ha⁻¹ in biomass carbon stock, respectively. The present study also revealed the relationship between woody perennial carbon stocks and the variables DBH, height, and stand density. Basal area) in cropland agroforestry practices (Fig. 5(a-d)). A relationship was estimated as: $y = 1.3344x - 7.6484$ ($R^2 = 0.3355$) where R^2 was positive, which indicates that the relationship was moderately strong (5% level of significance) between DBH and carbon stock. The equation also stated that carbon stocks increased at a rate of 1.3344 Mg ha⁻¹ per unit change of mean DBH (cm) (Fig. 5a). Similarly, carbon stocks increased at rates of 1.7739 Mg ha⁻¹, 1.2596 Mg ha⁻¹ and 1.3663 Mg ha⁻¹ per unit change of mean Height (m), density, and basal area (m² ha⁻¹) (Fig. 5(b-d)). Our findings agree with the earlier studies of various agroforestry systems and natural forest ecosystems. For example, Tamga *et al.* (2023) claimed that height and tree density showed a comparable coefficient of determination in agroforestry systems over three climatic regions in West Africa, which was $R^2 = 0.13$ and $R^2 = 0.1$, respectively. According to Roshni et al. (2023), the three sites' tree stand characteristics—height (m), DBH (cm), density (trees/ha), and basal area—strongly correlated with the biomass carbon stocks of the various tree species. Baul et al. (2021) reported that the total soil C stock was strongly correlated with tree structural composition, diversity, and soil properties. Biswas and Hasan (2020) stated that basal area and stand density/ha had a strong relationship with the above-ground biomass of the roadside agroforestry system in Mymensingh district, Bangladesh. The study states that the carbon content of woody species increases with an increase in average DBH. The study shows that there were more *Acacia auriculiformes*, *Gmelina arborea*, *Tectona grandis*, and *Swietenia macrophylla* plants in the forest land and plainland land ecosystems, which is why those areas had higher carbon stocks than the char land (Fig. 5). This finding is quite similar to the reported data by Baul et al. (2021), where the maximum number of individuals of *Samanea saman*, *Mangifera indica*, *Artocarpus heterophyllus*, and *Dipterocarpus turbinatus* in the hillside and inland homestead forests stored the highest amount of carbon. Alamgir and Al-Amin (2007) also found the largest quantity of biomass carbon from these similar tree species in the hill forests of Bangladesh. We found the highest SOC in the forest land ecosystem at two depths. The SOC was strongly correlated with stand structural composition and diversity indices, which have been referred to in the previous literature on tropical forests (Islam et al., 2015) and temperate forests (Chen et al., 2018; Schleu *et al.*, 2014). In a poplar-based agroforestry system, the maximum soil carbon stock was estimated (22.72 t ha⁻¹) in pattern C at 0–15 cm depth, as stated by Yasin et al. (2021). SOC content within 15 cm of soil depth in cropland agroforestry under a forest ecosystem is much greater because of higher litter fall rates, higher plant richness, and very low disturbance of soil (Saha *et al.*, 2008; Hossain *et al.*, 2021). Estimating the carbon stocks and species diversity of woody perennials has some potential implications for reducing carbon dioxide emissions under the REDD and its derivative programmes. Therefore, carbon storage in cropland agroforestry systems can provide co-benefits of biodiversity conservation as it aims to maintain carbon stock.

Conclusions

This study provides evidence on carbon stocks, structural composition, and diversity of woody perennials in cropland agroforestry practices at three land ecosystems in Bangladesh. The cropland agroforestry practices in the forest ecosystem stored a significant amount of biomass carbon stocks, which increased significantly with stand structural composition and diversity indices. The total carbon stock (AGC + BGC + SOC) of cropland agroforestry practices along land ecosystems indicates that these production systems have a high potential to sequester carbon stocks. The significant quantity of carbon stock observed in this study suggests that cropland agroforestry systems in various land ecosystems can combat global warming through sustainable ways of capturing atmospheric carbon. Furthermore, the study's analytical findings might be a source of carbon credits for landowners in developing nations like Bangladesh, while also producing livelihood alternatives and biodiversity protection in any land ecosystem.

Abbreviations

FLE
Forest land ecosystem
CLE
Char land ecosystem
PLE
Plain land ecosystem
AGC
Above ground carbon
BGC
Below ground carbon
DBH
Diameter at breast height
SOC
Soil organic carbon

Declarations

Accessibility of data and materials

The authors included all of the recorded or analyzed data used in this study.

Conflicts of interest

The authors affirm that no potential conflicts of interest exist here.

Funding

The funding for this study was provided by the Ministry of Science and Technology, Government of the People's Republic of Bangladesh (Reference No: 39.00.0000.009.14.019.21/BS-60/60, Project No: 2021/16/MoST)

Author Contribution

Each author has made substantial contributions to the development of this manuscript. M.K.H has made research conception and design, conducted analyses, interpreted data, and involved the preparation and revision of the manuscript. N.A.R has been in field data collection, organizing field data, and contributed to the analysis of soil, as well as participating in the manuscript

revision. R.A. was actively involved in critically drafting and revising the manuscript. All authors have reviewed and endorsed the final version of the manuscript.

Acknowledgments

The authors express their sincere appreciation to the Ministry of Science and Technology, Government of the People's Republic of Bangladesh for their financial assistance in the form of a research grant. The authors would like to express their heartfelt gratitude to the farmers and landowners of cropland agroforestry plots for their cooperation data collection and for their generous allocation of time. Additionally, the authors would like to acknowledge the Forest Department officials in the study area, specifically those in the Madhupur Sal forest, for their assistance in providing vital information pertinent to the research.

References

1. Agevi H, Onwonga R, Kuyah S, et al. Carbon stocks and stock changes in agroforestry practices: a review. *Trop Subtropical Agroecosyst.* 2017;20(1).
2. Akter R, Hasan MK, Kabir KH, Darr D, Roshni NA. Agroforestry systems and their impact on livelihood improvement of tribal farmers in a tropical moist deciduous forest in Bangladesh. *Trees, Forests and People.* 2022 Sep 1;9: 100315.
3. Alamgir M, Al-Amin M. Organic carbon storage in trees within different Geopositions of Chittagong (South) Forest Division, Bangladesh. *Journal of Forestry Research.* 2007 Sep;18:174-80.
4. 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.* Germany: Wiley; 2014
5. Alemu B. The role of Forest and soil carbon sequestrations on climate change mitigation. *Res J Agr Environ Manage.* 2014; 3:492–505.
6. Arora G, Chaturvedi S, Kaushal R, et al. Growth, bio-mass, carbon stocks, and sequestration in an age series of populus deltoides plantations in tarai region of Central himalaya. *Turk J Agric For.* 2014;38: 550–560.doi:10.3906/tar-1307-94
7. Bajigo, A., Tadesse, M., Moges, Y., and Anjulo, A. (2015). Monitoring of seasonal variation in physicochemical water parameters in Nalasopara region. *J. Ecosyst. Ecography* 5:157.
8. Baul TK, Chakraborty A, Nandi R, Mohiuddin M, Kilpeläinen A, Sultana T. Effects of tree species diversity and stand structure on carbon stocks of homestead forests in Maheshkhali Island, Southern Bangladesh. *Carbon Balance and Management.* 2021 Dec;16(1):1-5.
9. Baul TK, Peuly TA, Nandi R, Kar S, Mohiuddin M. Composition of homestead forests and their contribution to local livelihoods and environment: a study focused on Bandarban hill district, Bangladesh. *Trees, Forests and People.* 2021; Sep 1;5:100117.
10. BFD, (1999). Bangladesh Forest Department, Government of the People's Republic of Bangladesh. Available at <http://www.bforest.gov.bd> [last accessed on 30 December 2023]
11. Birhane E, Ahmed S, Hailemariam M, Negash M, Rannestad MM, Norgrove L. Carbon stock and woody species diversity in homegarden agroforestry along an elevation gradient in southern Ethiopia. *Agrofor Syst.* 2020; 94:1099–1110. doi: 10.1007/s10457-019-00475-4.
12. Biswas M, Hasan M. Measurement of above-ground carbon stocks of roadside agroforestry plantation at Sadar Upazila of Mymensingh district in Bangladesh. *J Bangladesh Agric Univ.* 2020;18: 252–259. <https://doi.org/10.5455/JBAU.911985455/JBAU.91198>.
13. Brown S. Estimating biomass and biomass change of tropical forests: a primer. *FAO Forestry Paper* 134. Rome: FAO; 1997.
14. Chakraborty M, Haider MZ, Rahaman MM. Socio-economic impact of cropland agroforestry: evidence from Jessore district of Bangladesh. *International Journal of Research in Agriculture and Forestry.* 2015 Jan;2(1):11-20.
15. Chauhan S, Sharma R, Singh B, et al. Biomass production, carbon sequestration and economics of on-farm poplar plantations in Punjab, India. *JANS.* 2015;7(1):452–458. doi:10.31018/jans. v7i1.631

16. Chave J, Andalo C, Brown S, Cairns MA, Chambers JQ, Eamus D, Fölster H, Fromard F, Higuchi N, Kira T, Lescure JP. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia*. 2005 Aug; 145:87-99. <https://doi.org/10.1007/s00442-005-0100-x>
17. Chave J, Coomes D, Jansen S, Lewis SL, Swenson NG, Zanne AE. Towards a worldwide wood economics spectrum. *Ecology letters*. 2009 Apr;12(4):351-66.
18. 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 USA*. 2018;115: 4027–32
19. Chowdhury MA, Islam KN, Hafiz N, Islam K. Diversity of trees in a community managed forest: The case of Komolchori VCF, Khagrachari, Bangladesh. *Geology, Ecology, and Landscapes*. 2019 Apr 3;3(2):95-103. <https://doi.org/10.1080/24749508.2018.1508980>
20. Dallmeier F. Methods for long-term biodiversity inventory plots in protected tropical forest. Long-term Monitoring of Biological Diversity in Tropical Forest Areas: Methods for Establishment and Inventory of Permanent Plot. 1992:11-46.
21. Das M, Nath PC, Reang D, Nath AJ, Das AK. Tree diversity and the improved estimate of the carbon storage for traditional agroforestry systems in north-East India. *Appl Ecol Environ Sci* 2020;8: 154–159.
22. Donahue RL, Miller RW, Shicklana JC 1987: An Introduction to Soils and Plant growth, 5th Edition, Prentice Hall of India Pvt. Ltd., New Delhi, India..
23. Food and Agriculture Organization, FAO. 2004. Community Forestry for Poverty Reduction in Bangladesh, In Proceedings of the Regional Workshop on Forests for Poverty Reduction: Can Community Forestry Make Money, Food and Agriculture Organization (FAO) of the United Nations, Regional Office for Asia and the Pacific, Bangkok, Thailand, p.197.
24. Ghosh SR, Wadud MA, Mondol MA, Rahman GM. Optimization of plant density of Akashmoni (*Acacia auriculiformis*) for production of fuel wood in the bunds of crop land. *Journal of Agroforestry Environment*. 2011;5(2):1-6.
25. Gupta DK, Bhatt R, Keerthika A, et al. Carbon sequestration potential of hardwickia binata roxb. based agroforestry in hot semi-arid environment of India: an assessment of tree density impact. *Curr Sci*. 2019;116(1):112–116. doi:10.18520/cs/v116/i1/112-116.
26. Hangarge LM, Kulkarni DK, Gaikwad VB, Mahajan DM, Chaudhari N. Carbon sequestration potential of tree species in Somjaichi Rai (Sacred grove) at Nandghur village, in Bhore region of Pune District, Maharashtra State, India. *Annals of Biological Research*. 2012;3(7):3426-9.
27. Hanif MA, Bari MS, Rahman Md A. Potentiality of agroforestry species to climate change mitigation through carbon sequestration. In Proceedings of 5th International Conference on Environmental Aspects of Bangladesh 2014.
28. Henry M, Tottonell P, Manlay RJ, Bernoux M, Albrecht A, Vanlauwe B. Biodiversity, carbon stocks and sequestration potential in aboveground biomass in smallholder farming systems of western Kenya. *Agriculture, ecosystems & environment*. 2009; Jan 1;129(1-3):238-52.
29. Hossain MF. Tree species diversity and carbon stock measurement: a study in char land homesteads in Sirajganj district of Bangladesh. *Journal of Agriculture, Food and Environment (JAFE)* ISSN (Online Version): 2708-5694. 2021 Dec 31;2(4):47-51. <http://doi.org/10.47440/JAFE.2021.2408>
30. IEA (International Energy Agency): <https://www.iea.org/countries/Bangladesh> (2020). Accessed 22 Jun 2020.
31. IPCC, Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems, Intergovernmental Panel on Climate Change, Geneva, Switzerland, 2019.
32. IPCC: Summary for policymakers 2018. In: Zhai P, Pörtner HO, Roberts D, Skea J, Shukla PR, Pirani A, Moufouma-Okia W, Pean C, Pidcock R, Connors S, Matthews JBR, Chen Y, Zhou X, Gomis MI, Lonnoy E, Maycock T, Tignor M, Waterfeld T, editors. Global Warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C 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.

33. Islam KK, Fujiwara T, Hyakumura K. Agroforestry, livelihood and biodiversity nexus: The case of Madhupur Tract, Bangladesh. *Conservation*. 2022 May 18;2(2): 305-21. <https://doi.org/10.3390/conservation2020022>
34. 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.
35. Islam MS, Tusher TR, Kabir MH, Hassan MR, Khan MN. Carbon storage and sequestration potentiality of tree species in Madhupur Sal Forest of Bangladesh. *Bangladesh J. Environ. Sci*. 2016;30(2012):33-9.
36. Jaman MS, Hossain MF, 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*. 2016;6: 169–80. Available from: <http://journal.sapub.org/ijaf>
37. Jose S, Bardhan S. Agroforestry for biomass production and carbon sequestration: an overview. *Agrofor. Syst*. 2012;86: 105–111. doi: 10.1007/s10457-012-9573-x.
38. Kabir, Md. Abid Ul. (2011). Investigation on the environmental suitability and sustainable rice productivity through system of rice intensification (SRI) at some selected Upazilas of Mymensingh district. 10.13140/RG.2.1.4321.0962.
39. Kanmegne Tamga, D.; Latifi, H.; Ullmann, T.; Baumhauer, R.; Bayala, J.; Thiel, M. Estimation of Aboveground Biomass in Agroforestry Systems over Three Climatic Regions in West Africa Using Sentinel-1, Sentinel-2, ALOS, and GEDI Data. *Sensors* 2023, 23, 349. <https://doi.org/10.3390/s23010349>
40. 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; 22:533–42.
41. Magurran AE. Ecological diversity and its measurement. Princeton university press; 1988 Nov 21.
42. Margalef R 1958: Information Theory in Ecology. *International Journal of General Systems* 3 36-71.
43. Misra R. Ecology Work Book Oxford and IBH Publishing Company. New Delhi. 1968.
44. 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.
45. Nair PR, Kumar BM, Nair VD, Nair PR, Kumar BM, Nair VD. Global distribution of agroforestry systems. An introduction to agroforestry: four decades of scientific developments. 2021:45-58. Springer, Cham. https://doi.org/10.1007/978-3-030-75358-0_4
46. Nair PR, Nair VD, Kumar BM, Haile SG. Soil carbon sequestration in tropical agroforestry systems: a feasibility appraisal. *Environmental Science & Policy*. 2009; Dec 1;12(8):1099-111.
47. Nawaz MF, Shah SAA, Gul S, et al. Carbon sequestration and production of eucalyptus camaldulensis plantations on marginal sandy agricultural lands. *Pak J Agric Sci*. 2017;54(02):335–342. doi:10.21162/ PAKJAS/17.4432.
48. Noponen MRA, Healey JR, Soto G, Haggard JP. Sink or source - The potential of coffee agroforestry systems to sequester atmospheric CO₂ into soil organic carbon. *Agriculture, Ecosystems & Environment*. 2013; 175:60–68.
49. Page AL, Miller RH, Keeny DR. Methods of soil analysis. American Society of Agronomy, Madison, Wisconsin, USA. 1989
50. Panwar P, Mahalingappa DG, Kaushal R, Bhardwaj DR, Chakravarty S, Shukla G, Thakur NS, Chavan SB, Pal S, Nayak BG, Srinivasaiah HT. Biomass production and carbon sequestration potential of different agroforestry systems in India: A critical review. *Forests*. 2022 Aug 12;13(8):1274.
51. Pearson TRH, Brown S, Ravindranath NH (2005) Integrating carbon benefits estimates into GEF. *Projects UNDP GEF*;1-56
52. Rahman MR, Hossain MK, Hossain MA. Diversity and composition of tree species in Madhupur national park, tangail, Bangladesh. *Journal of forest and environmental science*. 2019;35(3):159-72.
53. Roshni NA, Hasan MK, Akter R, Prodhan AK, Sagar A. Impacts of Industrialization on Plant Species Composition, Diversity, and Tree Population Structure in Tropical Moist Deciduous Forest in Bangladesh. *International Journal of Forestry Research*. 2022 Oct 4;2022.
54. Roshni NA, Hasan MK, Wadud MA, Hasan AK, Akter R, Khan RN, Hemel SA. Toxic Metal Levels in Forest Soils Caused by Industrialization and Impacts on Tree Biomass Carbon Stock. *Environmental Processes*. 2023 Sep;10(3):45.
55. Saha SK, Nair PR, Nair VD, Kumar BM. Soil carbon stock in relation to plant diversity of homegardens in Kerala, India. *Agroforestry systems*. 2009 May; 76:53-65.

56. Saleem I, Mugloo JA, Pala N, Baba AA, Mehraj B. Biomass production, carbon stock and sequestration potential of prominent agroforestry systems in North-western Himalaya, India. *Frontiers in Forests and Global Change*. 2023 Nov;6: 1192382.
57. Sarkar PK, Sarkar P, Kumar A. Carbon storage potential of a waterlogged agroforestry system of Tripura. India. *Water Air Soil Pollut* 2021;232: 232–151. doi: 10.1007/s11270-021-05098-z.
58. Sattar MA, Bhattacharje DK, Kabir MF. Physical and mechanical properties and uses of timbers of Bangladesh. Chittagong, Bangladesh: Bangladesh Forest Research Institute; 1999.
59. Schleuß P-M, Heitkamp F, Leuschner C, Fender A-C, Jungkunst HF. Higher subsoil carbon storage in species-rich than species-poor temperate forests. *Environ Res Lett*. 2014; 9:1–10. <https://doi.org/10.1088/1748-9326/9/1/014007>
60. Shams R. Socio-cultural impacts of agroforestry improvements in Narsingdi, Bangladesh. University of Alberta (Canada); 2013.
61. Shannon CE, Wiener W. The mathematical theory of communities. University of Illinois press, Urbana. 1963;117.
62. Shukla R, Chandel P (2000) Plant Ecology and Soil Science. Company Limited, New Delhi
63. Simpson EH 1949: Measurement of diversity. *Nature* 30 163-688.
64. Talukder MS, Miah MM, Miah MG, Haque MM, Rahman MM, Islam MM. Fruit tree-based agroforestry systems and their carbon sequestration potentials in different ecosystem of Bangladesh. *J Agrofor Environ*. 2019;13(1&2):43-8.
65. Tesfay F, Moges Y, Asfaw Z. Woody species composition, structure, and carbon stock of coffee-based agroforestry system along an elevation gradient in the moist mid-highlands of Southern Ethiopia. *Inter J For Research*. 2022 Jun 28;2022.
66. UNFCCC. Adoption of the Paris agreement. Geneva: Switzerland; 2015. p. 32.
67. Yadav R, Gupta B, Bhutia P, et al. Biomass and carbon budgeting of sustainable agroforestry systems as ecosystem service in Indian Himalayas. *Int J Sustainable Dev World Ecol*. 2019;26(5):460–470. doi: 10.1080/13504509.2019.1600597
68. Yasin G, Ur Rahman S, Farrakh Nawaz M, Qadir I, Zubair M, Gul S, Safdar Hussain M, Zain M, Athar Khaliq M. Estimating carbon stocks and biomass accumulation in three different agroforestry patterns in the semi-arid region of Pakistan. *Carbon Management*. 2021 Nov 29;12(6):593-602. DOI:10.1080/17583004.2021.1987332.

Tables

Table 1 is available in the Supplementary Files section.

Figures

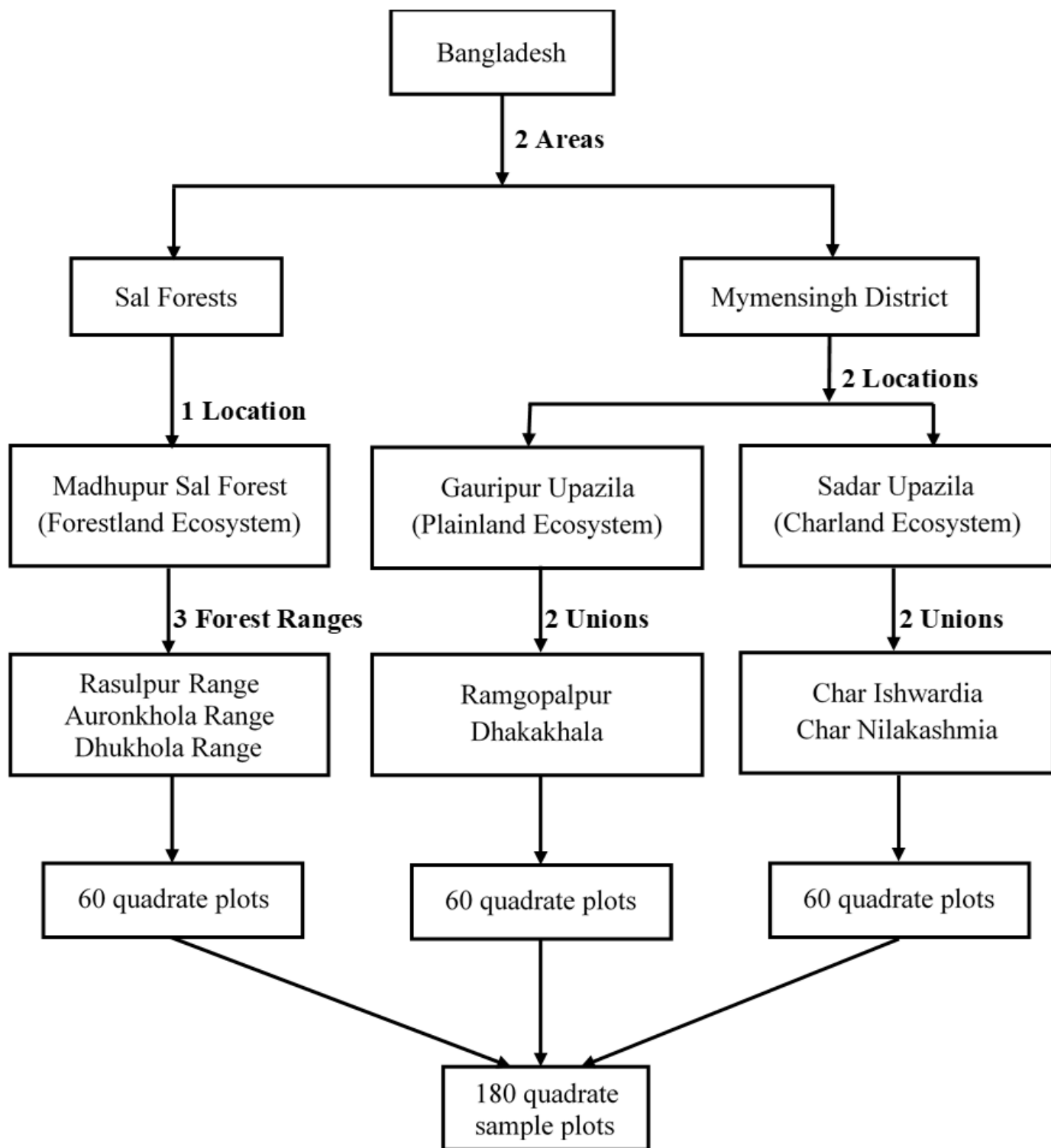


Figure 1

Map presenting the selected study sites; Madhupur Sal forest **(A)**, (Islam *et al.*, 2022) Gauripur Upazila **(B)** (Kabir, 2011) Mymensingh Sadar Upazila **(C)** (Ibrahim *et al.*, 2011)

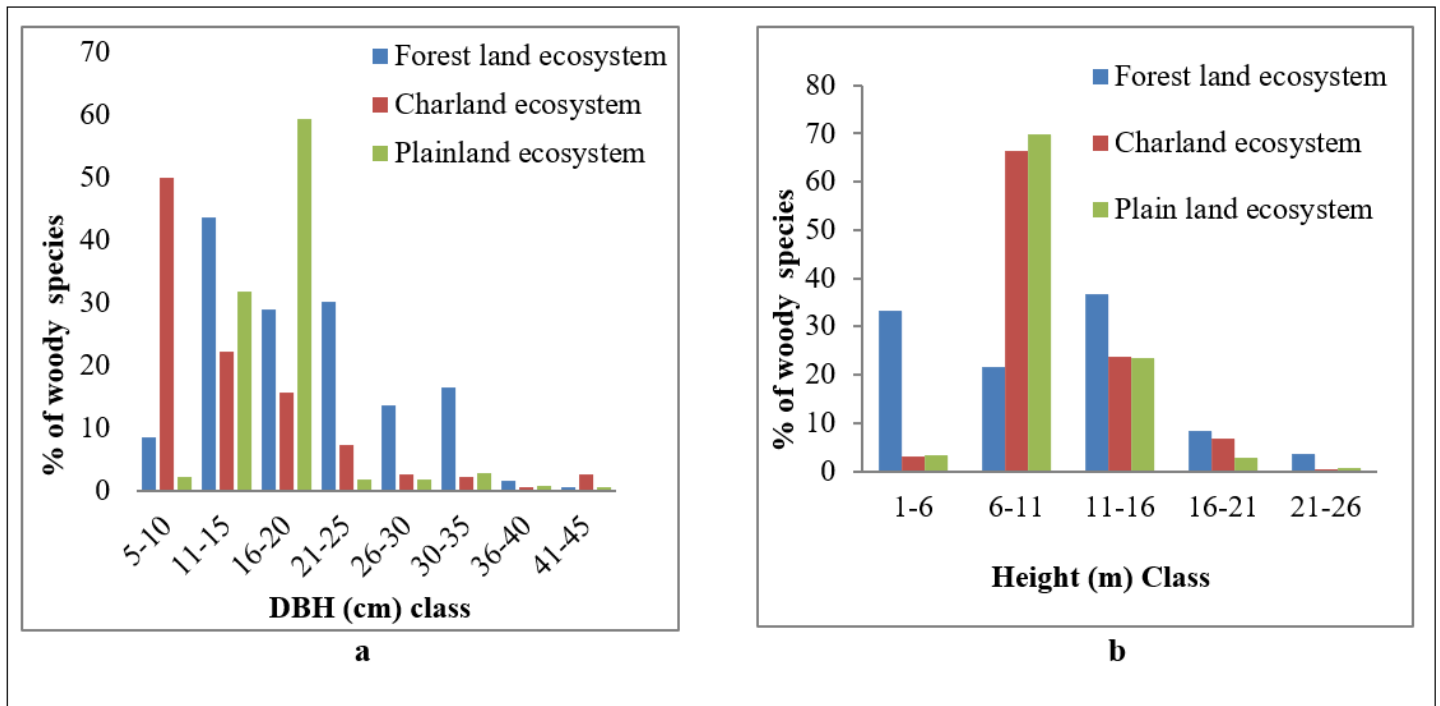


Figure 2

Sampling procedure for measuring woody perennials in cropland agroforestry in three different land ecosystems (Author constructed)

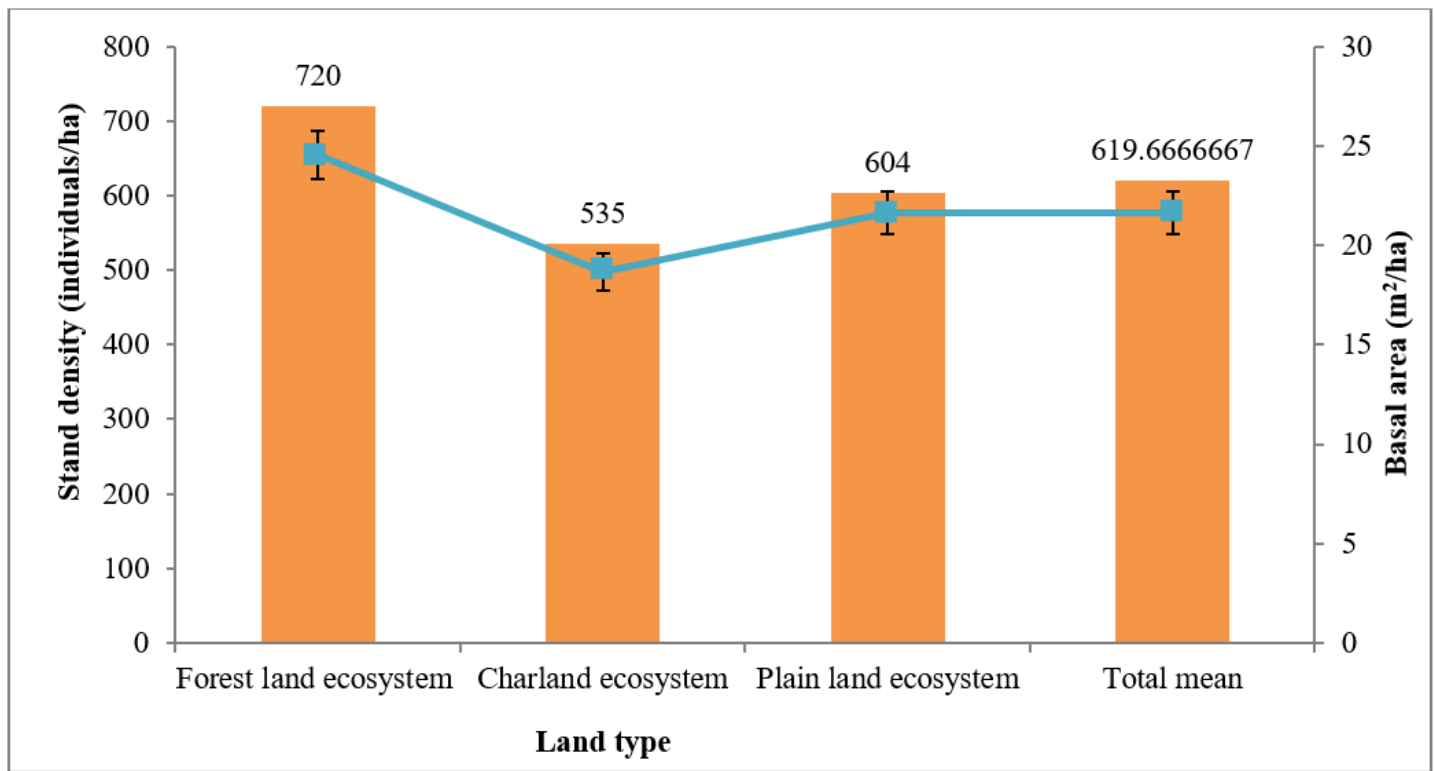


Figure 3

Stand density and basal area in the crop land agroforestry practices in three land ecosystems. Bars indicate standard error of mean.

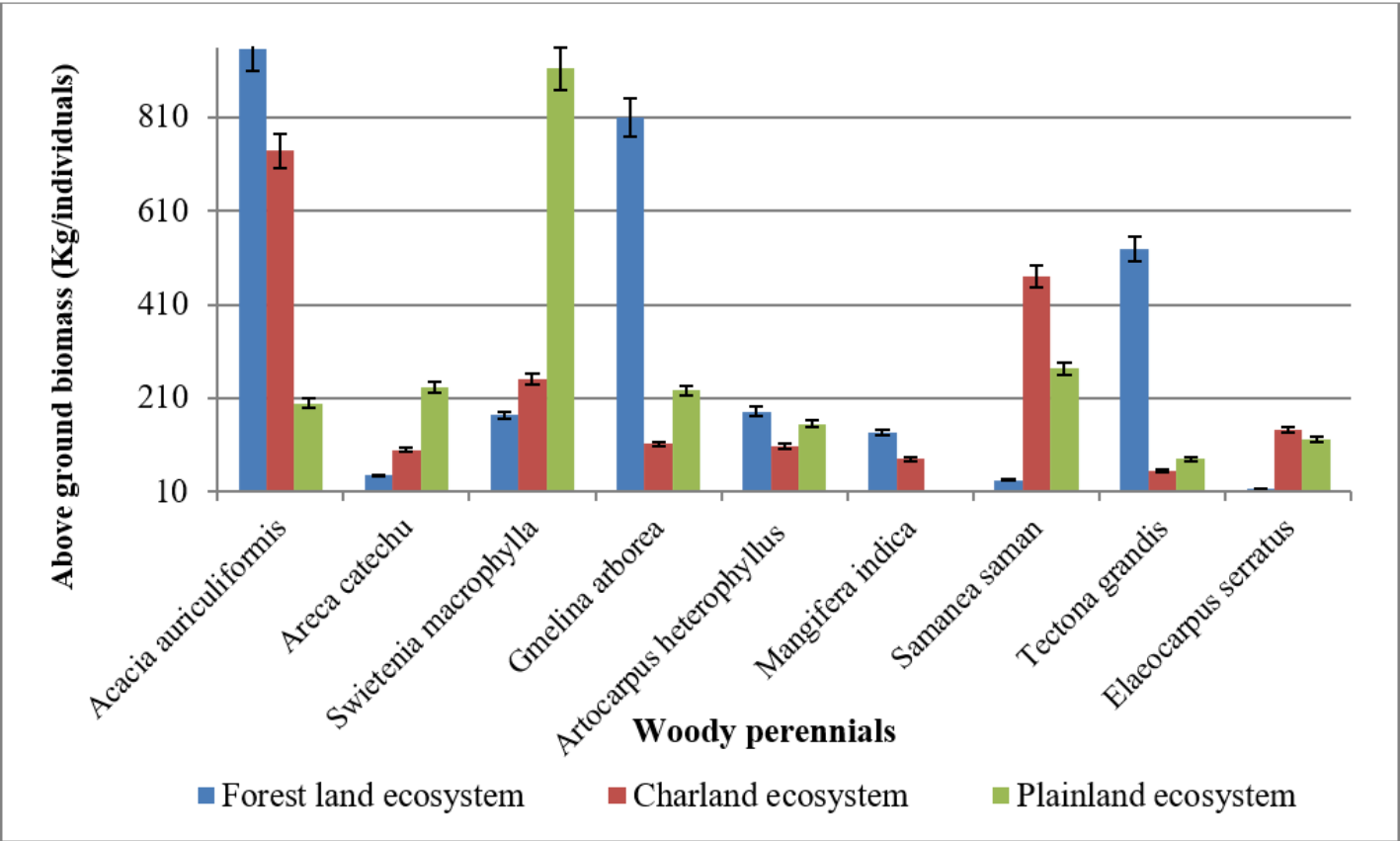


Figure 4
Above-ground biomass (AGB) for most abundant woody perennials in the cropland agroforestry at three land ecosystems.

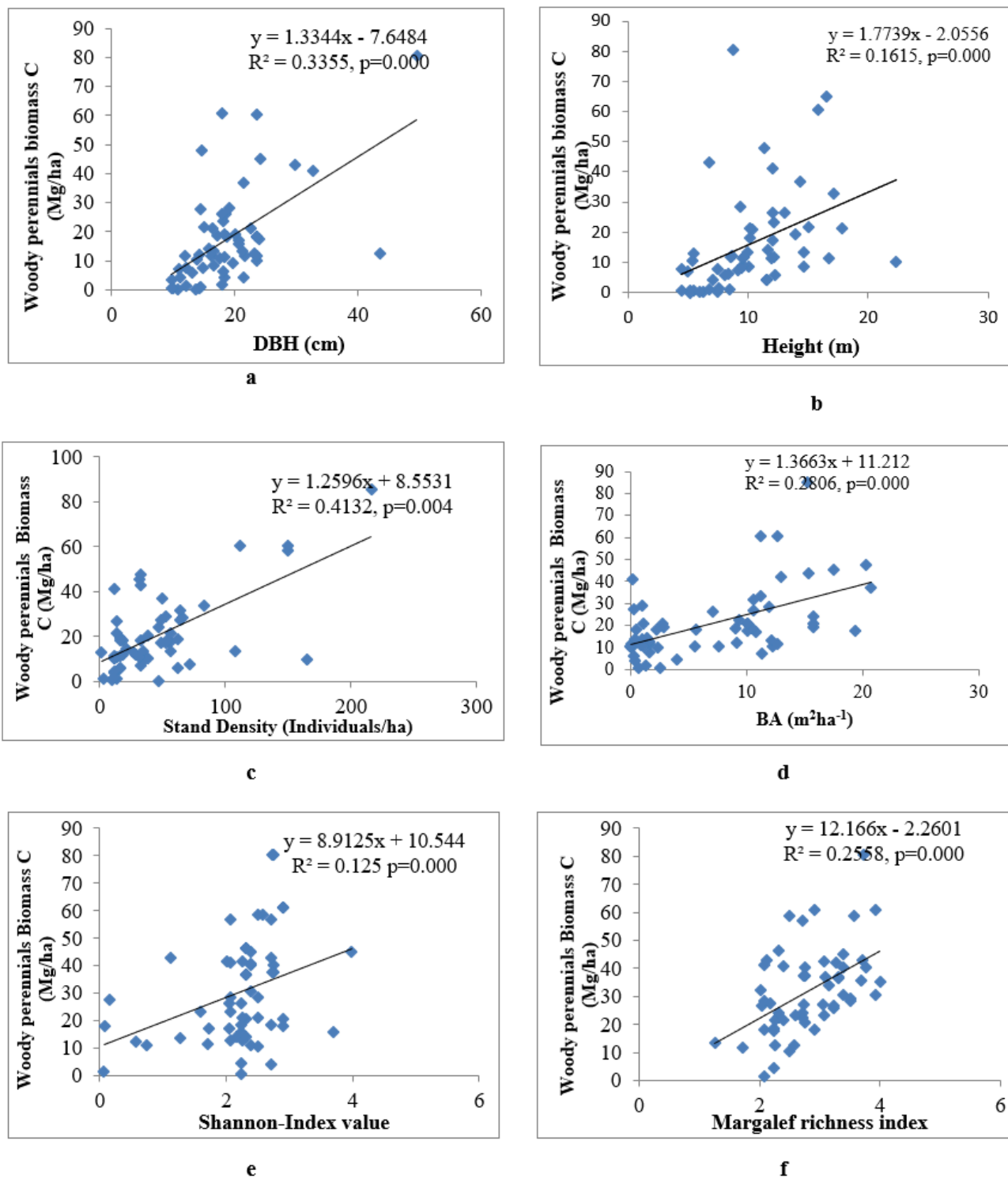


Figure 5

Relationship between woody perennials biomass carbon stocks and **(a)** DBH (cm), **(b)** Height (m), **(c)** Stand density, **(d)** BA ($m^2 ha^{-1}$), **(e)** Shannon–Wiener index and **(f)** Margalef’s richness index in the cropland agroforestry practices.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Table1.docx](#)