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Prioritizing Tree-Based Systems for Optimizing Carbon Sink in the Indian Sub-Himalayan Region

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Abstract: Land use of the sub-Himalayan region is not that intensive like the intensively land-managed region of Punjab, India. Land resources of the sub-Himalayas must be managed effectively for sustainable development by preparing carbon inventories and data banks. Such macro-level studies have not been conducted yet in the present study area, and thus were conducted to suggest sustainable land use management options. To achieve the present study's desired goal, 33 tree-based land uses were identified from forested and agricultural landscapes of the sub-humid tropical region of West Bengal, India. Stratified random nested quadrat sampling was adopted for the study. The SOC, biomass, and carbon accumulation significantly differed. Mixed forests had the highest soil primary nutrients and carbon stock. Positive correlations were observed between SOC, total standing biomass, litter production, and ecosystem carbon. The sequence of land uses based on carbon stock was mixed-species forest > sole tree species stands in a forest landscape > tea plantations > homegardens. This baseline information can be used for developing prediction models for future interventions towards sustainable land management. The study, however, could not estimate the carbon fluxes in and out of the systems due to the absence of detailed land use land-cover databases.

Keywords: land use; landscape; climate change; carbon; sub-humid tropic; Himalayas

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1. Introduction

A land use system directly reflects anthropogenic actions into the ecosystem and bridges the economy with the biosphere, mainly through agricultural and forestry management practices [1]. Land use changes in the form of deforestation, conversion of grassland to crop and pasture, and the depletion of soil carbon through agricultural practices during the last 150 years caused one-third of all anthropogenic CO_2 emissions, primarily responsible for affecting climate change [2–6]. Since the industrial revolution, land use change has altered a large proportion of the earth's land surface resulting in the emission of 150 billion metric tons of carbon, which is 35% of the total anthropogenic CO_2 emissions [1,7,8]. Unabated land use changes are expected to release another 10% of all CO_2 during the next century [9]. Climate change is one of the present century's significant issues responsible for reducing biological diversity and the ability of biological systems to support human needs by altering ecosystem services [10,11]. An increased concern about climate change risk has led local to global efforts for its viable mitigation through proper land management activities, which can double the carbon storage potential of the sink [12–15]. Land use and land cover change (LUCC) is critical to understand the spatial distribution, magnitude, and temporal change of terrestrial carbon sources and sinks [16–18], but neither has been comprehensively studied nor estimated for the Indian sub-Himalayan region.

Studies have reported the relationship between plant diversity and carbon storage [19–21] and the essential role of carbon sequestration by trees and soil for low-cost net emission reduction [22,23]. Soil organic matter and biomass production by vegetation and soil play an important role in the carbon cycle and are regarded as vital for their capacity to store carbon permanently and improve the local or regional and global environments [20,21,24]. In the humid tropics, the establishment of tree-based systems on degraded pastures, croplands, and grasslands would increase biomass carbon storage by 50 Mg ha^{-1} in 20 years, when compared to 5–15 Mg ha^{-1} in soils during the same period [25]. This indicates that carbon sequestration measures can considerably mitigate climate change by storing carbon in terrestrial carbon sinks like plants, plant products, and soils for a longer duration [20,21]. Thus, terrestrial carbon management is the most viable and effective strategy of the 21st century to mitigate global climate change. The tropical soils are low in organic carbon content and, in principle, have a large potential to sequester carbon through appropriate land and crop management options [26]. Therefore, biomass and soil carbon storage quantification are the most relevant in analyzing the total soil carbon sink and formulating management options at local, regional, and global levels to mitigate climate change.

The assessment of carbon storage potential has been complex due to a lack of information on biomass compartmentation and carbon allocation in different species [27,28], particularly the native species. Similarly, due to their high spatial variability, the soil carbon pool under tree-based landscapes is highly dynamic and thus difficult to analyze [29,30]. The literature survey revealed fewer comprehensive studies on land use management for climate change mitigation through tree-based land use management systems from the Terai region of West Bengal. Distribution and carbon storage changes are vital to understanding process and planning management [31,32]. Climate change and land use management studies were mainly descriptive at higher spatial scales, i.e., regional, national, and global [33,34]. There is a need to change the trend to locally convenient landscapes where land use decisions and management policies are implemented. The potential of carbon storage differs with different land use systems and their management practices because biomass production capacity and soil organic matter are the functions of site-specific interactions among edaphic, climatic, and topographic factors [35]. Hence, management strategies in one place may not apply to another. Therefore, site-specific studies on land use systems for quantifying carbon storage are essential.

Land resources have been under tremendous anthropogenic pressure due to their degradation. Land uses of the Indian sub-Himalayan region (Terai region of West Bengal) have been extensively managed and have the potential to enhance carbon sequestration, provided the land resources of this region are managed efficiently. Unlike in developed countries, carbon inventories and data banks to monitor the carbon sequestration potential of different ecosystems still need to be prepared for the Indian sub-Himalayan region. Moreover, carbon sequestration studies for diverse land uses are scarce from this region [20,21,36–38]. Such micro-level studies are essential for sustainable land use management for a country like India, and especially for the Terai region of West Bengal, to recommend suitable land use management prescriptions for carbon management and meeting the local and national needs. Thus, the present study was conducted to assess the suitability of different tree-based land use systems as alternatives to continuous cropping through the system's ability to sequester and store carbon and to identify the most appropriate land use system based on carbon stock.

2. Methodology

2.1. Study Site

The study site was the Terai zone, i.e., the foothills and plains area of the Himalayas in the northern part of West Bengal, which lies between 26°30′ and 26°56′ N latitude and 88°7′ and 89°53′ E longitude (Figure 1).

The region is sub-tropical, receiving an average annual rainfall of 250–300 cm from south-west monsoons, of which 80% was received from June to August. The region has net sown area, forest area, and non-agricultural use as 56.13, 24.05, and 15.68%, respectively, of the total geographical area (bengalchamber.com/economies/west-bengal-statistics). The dominant crops are jute (*Corchorus olitorius*), paddy (*Oryza sativa*), and tobacco (*Nicotiana tabacum*). Plantation crops grown in the region are tea and areca nut. The area under tea cultivation is about 2000 km^2 (www.jalpaiguri.gov.in, accessed on 1 March2023). A vast population in the district is directly or indirectly dependent on its forest for their livelihood.

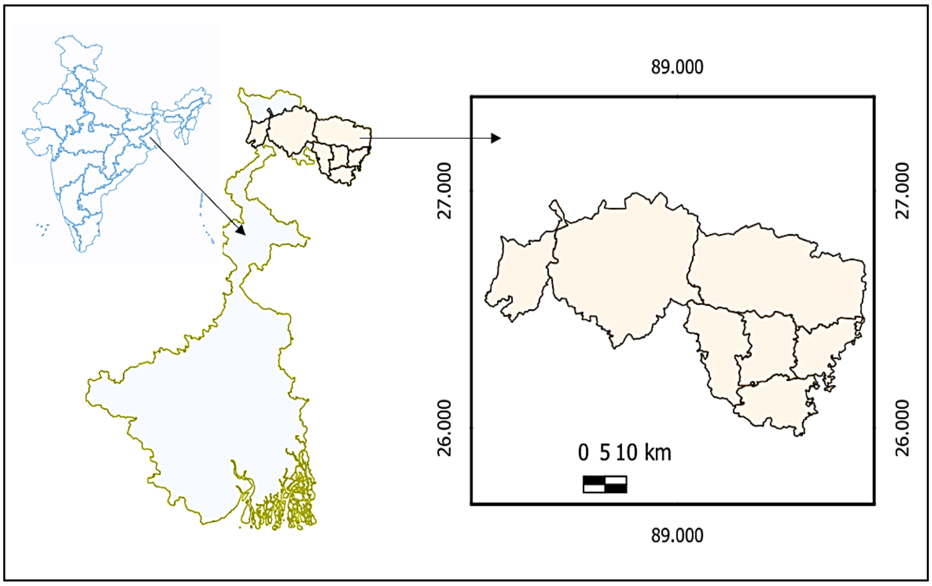


Figure 1. Layout map of Terai region, West Bengal.

The study area was extensively explored, and 33 tree-based land uses were identified for the present study. These land uses were categorized into five major land use systems: forest, forest tree plantations, agroforestry, commercial crop plantation, and fruit orchard. Other than forests, all other tree-based land use systems were on the agricultural landscape. The sampling details are given in Table 1. According to the landowners, the plantations in the agricultural landscape were about 15–20 years of age. Samples were collected from all the above-mentioned tree-based land use systems, and the data were presented on an average for a particular land use category. This study did not consider biomass produced by annual crops.

Table 1. Sampling details of tree-based land uses.

Tree-Based Land Use System	Number of Quadrats
I. Forest landscape	50
1. *Lagerstroemia parviflora* stand	10
2. *Michelia champaca* stand	10
3. *Tectona grandis* stand	10
4. *Shorea robusta* stand	10
5. Mixed-species forest	10
II. Agricultural Landscape	150
i. Forest Tree Plantation	70
6. *Swietenia macrophylla*	10
7. *Anthocephalus cadamba*	10
8. *Gmelina arborea*	10
9. *Shorea borneensis*	10
10. *Tectona grandis*	10
11. *Lagerstroemia indica*	10
12. *Tectona grandis* + *Milvus migrans*	5
13. *Anthocephalus cadamba* + *Swietenia macrophylla*	5

Table 1. *Cont.*

Tree-Based Land Use System	Number of Quadrats
ii. Agroforestry	34
14. *Albizia lebbeck* based	3
15. *Swietenia macrophylla* based	3
16. *Terminalia arjuna* based	3
17. *Gmelina arborea* based	3
18. *Millettia pinnata* based	3
19. *Lagerstroemia indica* based	3
20. *Anthocephalus cadamba* based	3
21. *Mangifera indica* based	3
22. Homegardens	10
iii. Commercial Crop Plantation	30
23. *Hevea brasiliensis*	3
24. *Cocos nucifera*	3
25. *Areca catechu*	10
26. *Machilus bombycina* (*Som*)	4
27. Tea plantations	10
iv. Fruit Orchard	18
28. *Psidium guajava*	3
29. *Manilkara zapota*	3
30. *Litchi chinensis*	3
31. *Anacardium occidentale*	3
32. *Citrus lemon*	3
33. *Mangifera indica*	3
Total sample size	200

Agrisilvicultural systems of sole or mixed tree species, tree fruit orchards, coconut plantations, rubber plantations, and *Machilus* plantations are not common in the region. Except *Machilus*, all these plantations were planted in the Uttar Banga Krishi Viswavidyalaya campus, Pundibari for research and demonstration purposes to popularize agroforestry practices among the farmers. *Machilus* was planted by the State Silk Board at their experimental area for demonstration to popularize silk cultivation in the region. *Machilus* plantations were not found elsewhere during the survey. The sample size of these plantations was thus much smaller.

2.2. Sampling and Sample Collection

A stratified random nested quadrat sampling was adopted for collecting vegetation data. A quadrat size of 20 m × 20 m was used in the present study for trees, within which two 5 m × 5 m quadrats were laid out at the diagonal corners for shrubs, five 1 m × 1 m quadrats at the four corners, and one at the center of the 20 m × 20 m quadrat for herbs. Composite soil samples were collected once separately from 0–20, 20–40, 40–60 cm depth with the help of Dutch augur (locally prepared) from all the quadrats. Soil samples were separately collected from three different spots (separately for given depths) placed diagonally (two on the corners and one at the center). The collected samples from the different spots for the given depths were mixed to make the composite sample. In addition, litter was collected once from three 1 m × 1 m sub-quadrats placed diagonally (two at opposite corners and one in the center) within the main quadrat [39]. The litter collected was weighed in the field itself with a weighing balance.

2.3. Diameter and Height

The diameter (at breast height) and their standing height for the trees were measured with the help of a tree caliper and Ravi's Multimeter, respectively.

2.4. Soil Physical and Chemical Parameters

The different soil physical and chemical parameters were analyzed following the method given below.

pH	Beckman's pH meter [40]
Moisture	Volumetric method [41]
Bulk density	Core sampler method [41]
Electrical conductivity	Soil water suspension [40]
Oxidizable organic carbon (%)	Walkley and Black's rapid titration method [40]
Available N Kg ha^{-1}	Modified Kjeldahl method [40]
Available P_2O_5 Kg ha^{-1}	Bray's method [40,42]
Available K_2O Kg ha^{-1}	Flame Photometer method [40]

2.5. Soil Organic Carbon Stock

The soil organic carbon stock was calculated by multiplying the organic carbon content with weight of the soil (bulk density and depth) for a particular soil depth, and was expressed as mega grams per ha (Mg ha^{-1}).

2.6. Biomass and Biomass Carbon

An indirect or non-destructive method was adopted for biomass estimations. Tree biomass was estimated for each individual tree and then summed up:

$$\text{All tree: } Y = \exp\{-2.134 + 2.350 \times \text{In}(D)\}$$

where Y = biomass per tree, exponential function, D = diameter at breast height in cm. This equation predicts the trunk and canopy biomass of the moist (1500–4000 mm rainfall) area with reasonable precision ($R^2 = 0.97$) and has become a standard approach [43].

The biomass of coconut palm was estimated using the equation suggested by Kumar [44]:

$$Y = 5.5209x + 89.355$$

where $R^2 = 0.89$, Y = biomass, x = Palm age in year.

The biomass of areca palm was estimated using the equation suggested by Brown [45]:

$$Y = 4.5 + 7.7\ H$$

where Y = biomass and H = stem height in meters.

The biomass of tea was estimated using equations suggested by Kalita et al. [46,47]:

$$AGB = 0.047 \times (\text{diameter})^{1.878};\ BGB = 0.014 \times (\text{diameter})^{1.870}$$

Five shrubs were randomly selected from every 5 m × 5 m sub-quadrat and uprooted to measure their average fresh weight and then multiplied by the total number of shrubs in the quadrat. For herbs, all the plants from five 1 m × 1 m sub-quadrats were uprooted to measure their fresh weight. The total biomass estimated in a quadrat was converted into carbon by multiplying it with a factor of 0.50 [9]. The total of standing biomass carbon (trees + shrubs + herbs), litter carbon, and oxidizable carbon up to 60 cm soil depth was considered as the ecosystem carbon storage.

2.7. Statistical Analysis

The data were analyzed using the software package SPSS version 17.0 (VSN International, Oxford, UK) and SAS. A Pearson correlation test was performed at 0.05 (*) and 0.01 (**) probability levels. One-way variance analysis and a Duncan multiple range test (DMRT) test were also employed.

3. Results and Discussions

3.1. Soil Organic Carbon (SOC) Storage in Relation to Different Land Uses

The SOC (oxidizable) stock in different tree-based land use systems at different soil depths is given in Supplementary Table S1 and Figure 2. The tree-based land use systems and their soil depth significantly influenced SOC stock. SOC is influenced by the complex interaction of geographic location, rainfall, soil texture, and land use practices [48]. In all the tree-based land use systems, the topmost soil layer (0–20 cm) was estimated with the highest amount of SOC stock that decreased significantly with an increase in soil depth.

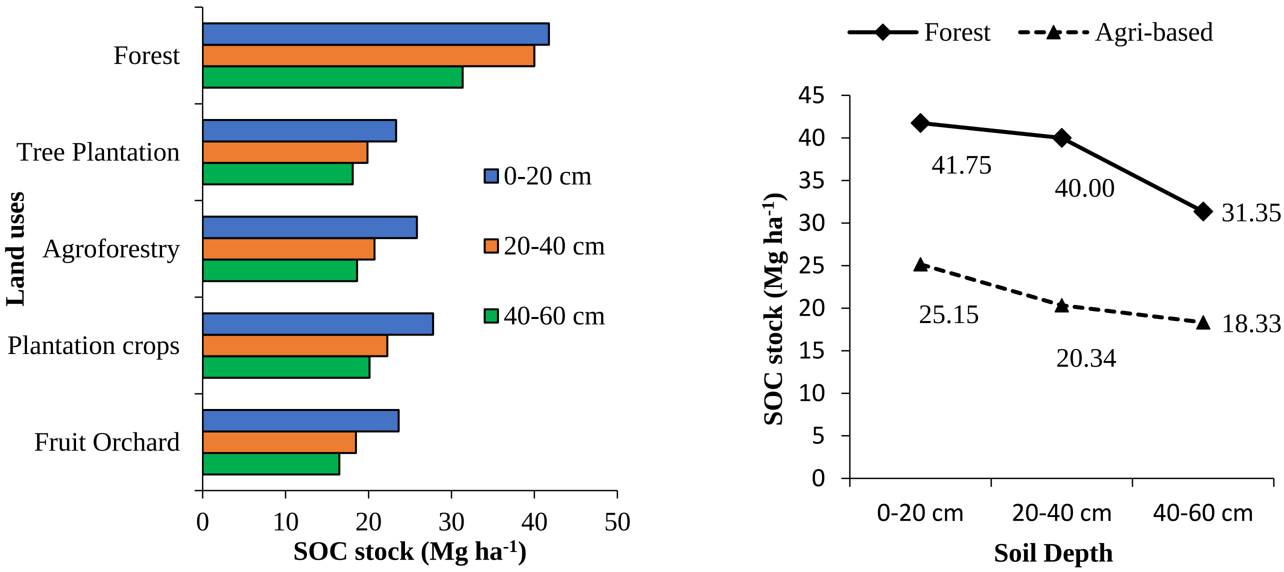


Figure 2. Effect of land uses and soil depth on soil organic carbon.

This trend is due to the gradual decrease of organic matter with increasing soil depth [20,21,49–52]. The range of SOC stock estimated for the entire tree-based land use systems of the Terai zone of West Bengal was 22.55–47.06 Mg ha^{-1}, 18.15–47.13 Mg ha^{-1}, and 16.18–32.90 Mg ha^{-1} at 0–20 cm, 20–40 cm, and 40–60 cm soil depth, respectively. The mixed-species forest land use was estimated with the highest amount of SOC stock at all the soil depths, which was significantly higher than all other tree-based land use systems. Overall, on an average (hectare basis), homegardens and tea plantations were estimated with 40.22% and 22.73% less SOC stock than mixed-species forest systems, respectively. On average, tree-based land use systems in forested landscapes accumulated 78.2% more SOC for a unit area than tree-based land use systems in agricultural landscapes.

Among the tree-based land use systems in the agricultural landscape, the SOC stock of forest tree plantations, agroforestry systems, commercial crop plantations, and fruit orchards was estimated with an overall average range (up to 60 cm soil depth) and overall mean of 20.0–21.53 Mg ha^{-1} and 20.43 Mg ha^{-1}; 20.19–30.11 Mg ha^{-1} and 21.61 Mg ha^{-1}; 20.02–34.4 Mg ha^{-1} and 23.39 Mg ha^{-1}; and 19.15–20.01 Mg ha^{-1} and 19.53 Mg ha^{-1}, respectively. Thus, the order of tree-based land use systems in terms of its overall mean estimated SOC accumulation in Terai zone of West Bengal is forests > commercial crop plantations > agroforestry systems > forest tree plantations > fruit orchards. Forests accumulated on an average 84%, 74%, 61%, and 91% more SOC than forest tree plantations, agroforestry systems, commercial crop plantations, and fruit orchards, respectively. In the agricultural landscape, the selected forest tree plantations were more or less statistically similar in terms of their SOC accumulation. Similarly, the different fruit orchards also accumulated statistically similar amounts of SOC. However, in agroforestry systems, homegardens were estimated with significantly higher amount of overall average SOC (up to 60 cm soil depth) than all other agroforestry systems like agri- or hortisilviculture systems (Supplementary Table S1). Similarly, among the commercial crop plantations, tea plantations accumulated a significantly higher amount of overall average SOC (up to 60 cm soil depth). Similar amounts of SOC in different land use systems were also reported by earlier studies from the Terai zone of West Bengal [20,21,48–54], with the highest in forest soils [53–56].

The high SOC storage in forest soil is due to the high litter addition of 13.6 Mg ha^{-1} (Supplementary Table S2) which regulated organic matter decomposition and the formation of a stable and liable soil organic matter pool [57,58]. On the other hand, the amount of SOC decreased with the soil depth in all the tree-based land use systems due to humus formation and the decomposition of organic matter in the upper layers. Therefore, SOC storing is vital to conserve and restrict carbon emissions. The average total SOC estimate of 113.09 Mg ha^{-1} in forestland up to 60 cm soil depth is similar to that reported for other tropical, moist deciduous forests in India, i.e., 8.9–176.1 Mg ha^{-1} for top 50 cm depth [59]. Based on major land uses, the highest mean SOC density in Indian soils under plantation systems was 253 Mg C ha^{-1}, followed by forest (139.9 t C ha^{-1}) and agricultural land (58.5–67.4 Mg C ha^{-1}) [60]. The SOC storage between tree-based land uses in the Terai zone of West Bengal differed significantly. Thus, land use conversion from a higher SOC stock to a lesser one will cause significant terrestrial carbon emissions, reducing the potential for land sustainability [61]. Soil carbon sequestration through tree-based land use practices is thus an effective mitigation option to increase its carbon for agricultural productivity and sustainability and mitigate climate change [62,63]. Land use conversion from forest to agriculture can reduce more than half of the SOC stock of the system but converting to homegarden or coffee, mango, coconut, or areca nut-based agroforestry systems or a sole areca nut system on agricultural land can increase the SOC stock of the system [64].

3.2. Soil Electrical Conductivity, Moisture and pH

Soil depth and land use systems significantly influenced the soil's electrical conductivity (EC), pH, and moisture (Supplementary Tables S3–S5 and Figures 3–5). The soil depth and land use systems significantly influenced the soil electrical conductivity (EC), pH, and moisture. EC decreased significantly with increasing soil depth for all the tree-based land use systems, while the soil pH and moisture increased with the increase in soil depth. The soil under all the land use systems was acidic. Soil organic matter is mainly responsible for regulating the soil's physical and chemical properties [65]. Generally, low pH in tree-based systems is due to higher organic matter accumulation [66] that results in high SOC with the leaching of bases and an increase in the soil EC [67]. On the other hand, higher EC and moisture of soils lower their pH [67].

The reduction in pH can be attributed to the accumulation and subsequent slow decomposition of organic matter, which releases acids [68]. This explains the more acidic nature of forest soils compared to the soils of other tree-based land use systems in which more soil organic matter is added through litter production. Forests soils, especially with mixed species, accumulated maximum soil organic matter compared to the other tree-based land use systems and thus were most acidic [20,21,51,52]. The surface layer was significantly more acidic than the sub-surface layers in all the tree-based land use systems. This is because of more organic matter in the form of litter in the top layer led to the surface soil floor's acidic nature. The study area is humid and receives high rainfall. Humidity influences water retention directly by reducing evaporation rates and increasing water infiltration [69]. The undisturbed and continuous canopy of the forests' stands intercepted most of the solar radiation, causing less evaporation and thereby conserving high soil moisture compared to other tree-based land use systems. Moreover, higher soil organic matter in the form of litter and humus absorbed and held substantial quantities of water, up to 20 times its mass in forest soil [70]. The continuous canopy and higher moisture retention capacity of forest soils compared to the soils of other tree-based systems help reduce the evaporation rates and water infiltration to the groundwater layers.

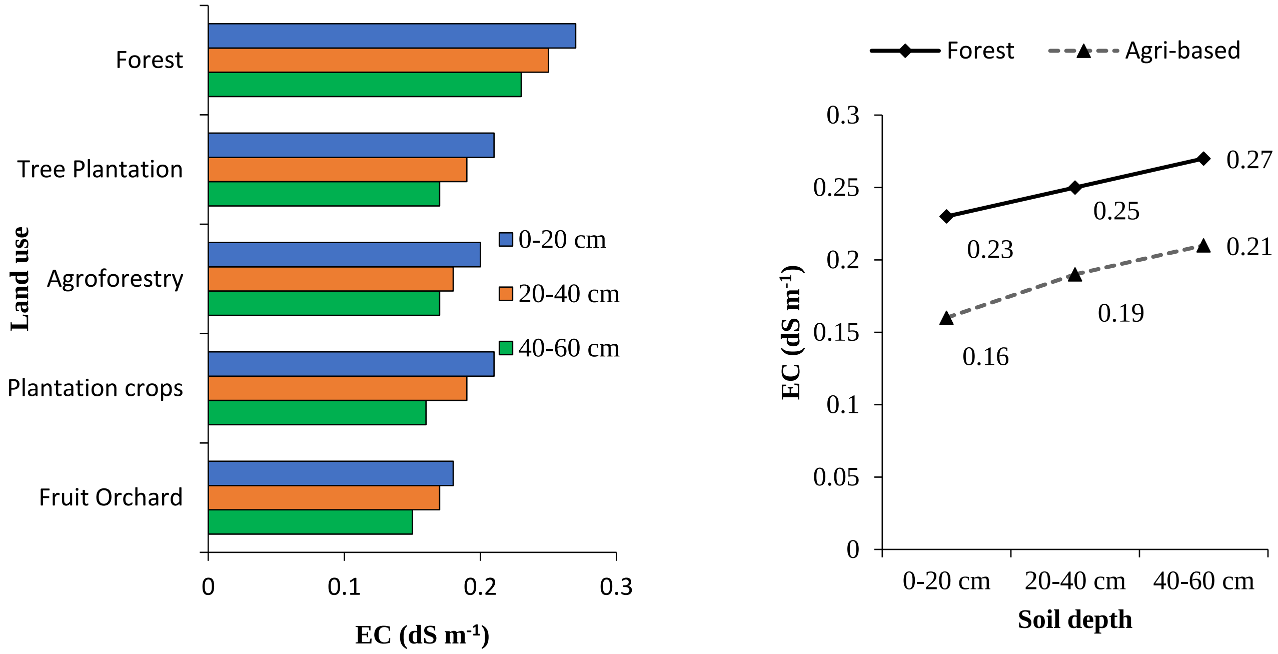


Figure 3. Effect of land uses and soil depth on soil electrical conductivity.

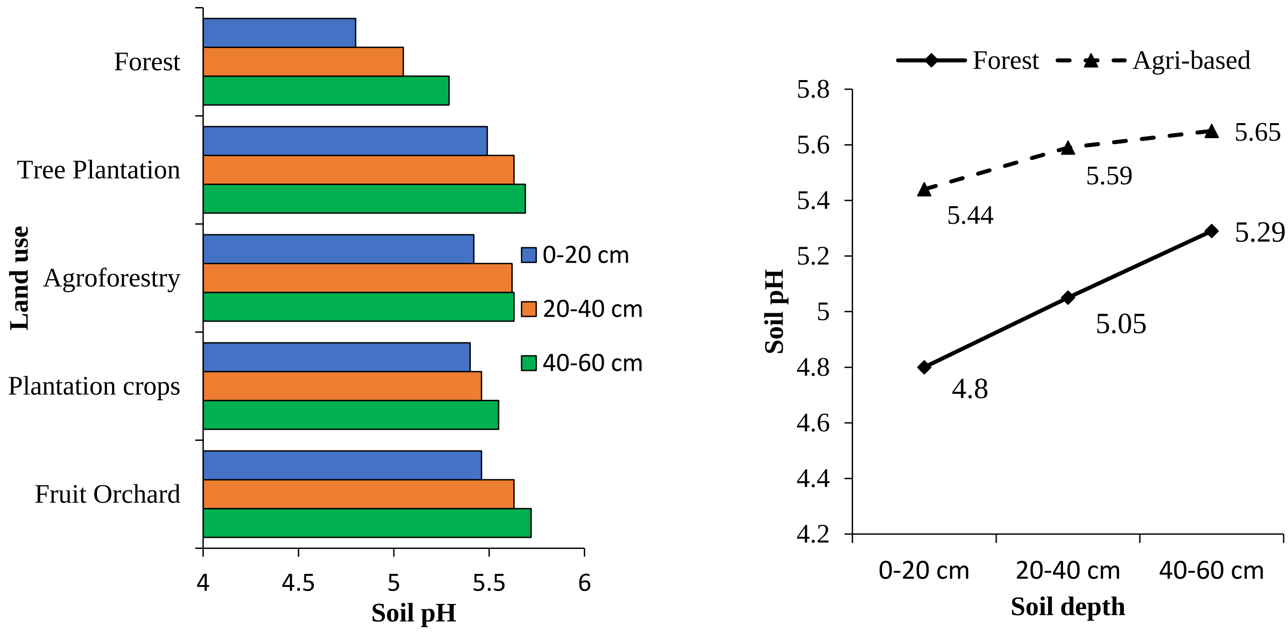


Figure 4. Effect of land uses and soil depth on soil pH.

3.3. Soil-Available Primary Nutrients

3.3.1. Nitrogen

The soil-available nitrogen in different tree-based land use systems at different soil depths are given in Supplementary Table S6 and Figure 6. Tree-based land use systems and the soil depth significantly influenced the soil-available nitrogen. The soils of mixed-species forests were estimated with the highest available nitrogen at all the soil depths. They were significantly higher than the estimated available nitrogen of other tree-based land use systems. On an average, the mixed-species forest stored 12.79% more available nitrogen (on a hectare basis) than *Shorea robusta* stands, 17.03% more than *Lagerstroemia parviflora* stands, 17.64% more than *Michelia champaca* stands, and 21.81% more than *Tectona grandis* stands. This was 11.48% more than homegardens and 42.24% more than tea plantations.

The ordering of tree-based land use system in terms of mean estimated available nitrogen in Terai zone of West Bengal is forests > fruit orchards > agroforestry systems > commercial crop plantation > forest tree plantations. Forest land use systems accumulated on an average 49.65%, 37.6%, 45.08%, and 31.27% more soil-available nitrogen than forest tree plantations, agroforestry systems, commercial crop plantations, and fruit orchards, respectively.

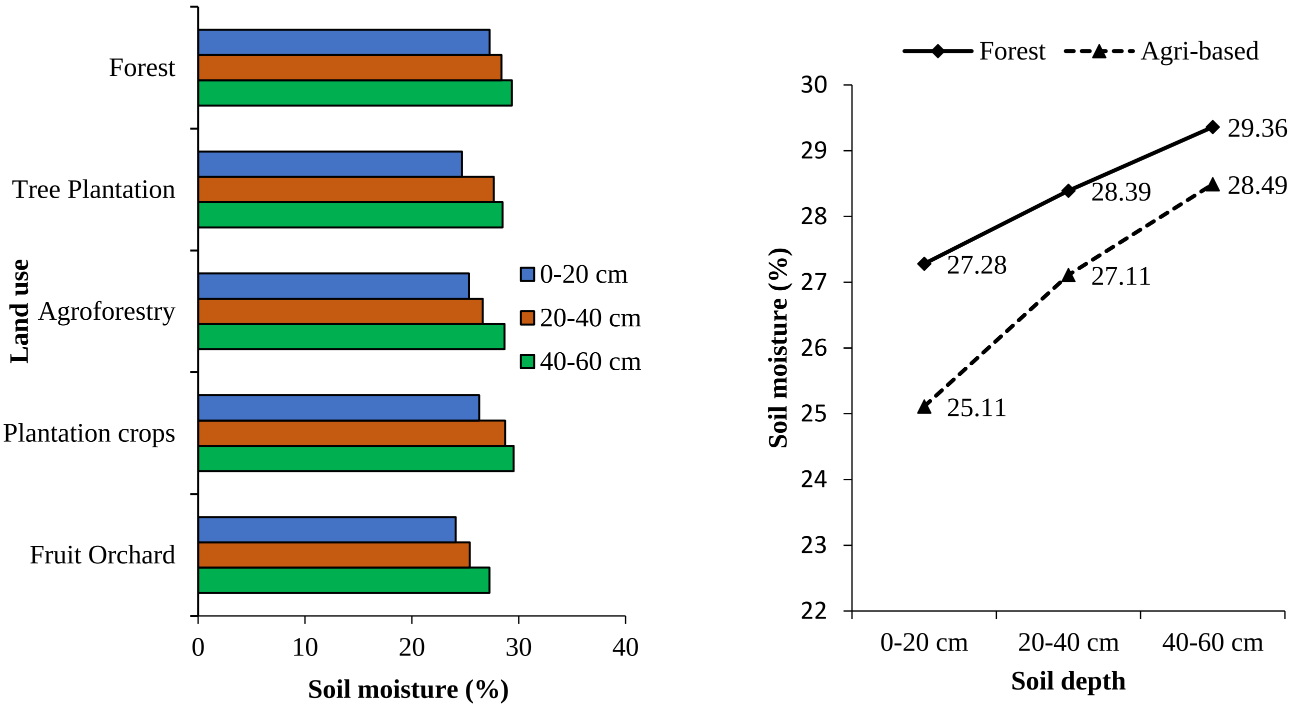


Figure 5. Effect of land uses and soil depth on soil moisture.

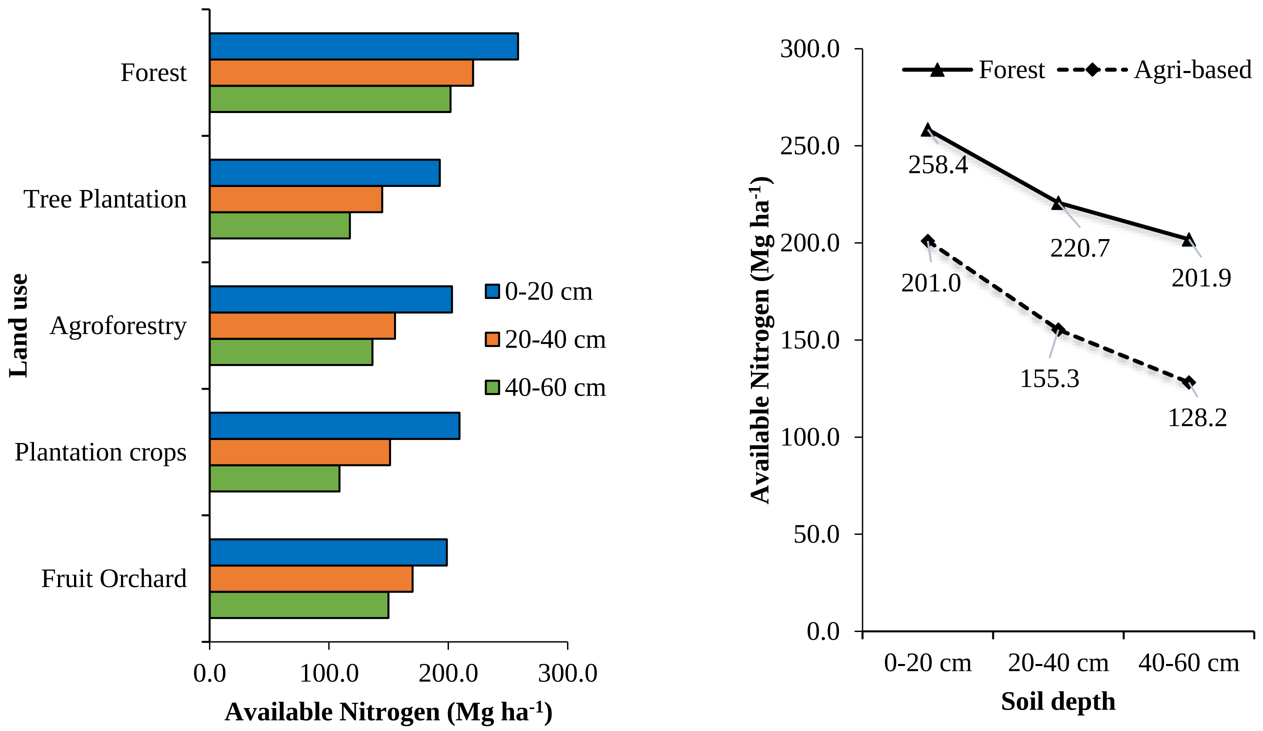


Figure 6. Effect of land uses and soil depth on soil-available nitrogen.

3.3.2. Phosphorus

The available phosphorus estimated for different tree-based land use systems at different soil depth is given in Supplementary Table S7 and Figure 7. Tree-based land use systems and the soil depth significantly influenced the soil-available phosphorus. The highest soil-available phosphorus was found in forests at all the soil depths and was significantly higher than those estimated for other tree-based systems, except the homegardens. The overall average available phosphorus (up to 60 cm soil depth) stored by tree-based land use systems in the agricultural landscape was 15.99 kg ha^{-1}, i.e., 38.52% less than what was stored in the forests. In the agricultural landscape, tea plantations stored a significantly higher amount of available phosphorus (52.64–64.08%) than other tree-based systems. In Terai zone of West Bengal, the ordering of tree-based land use system in terms of overall soil phosphorus availability is forests > commercial crop plantations > forest tree plantations > agroforestry systems > fruit orchards.

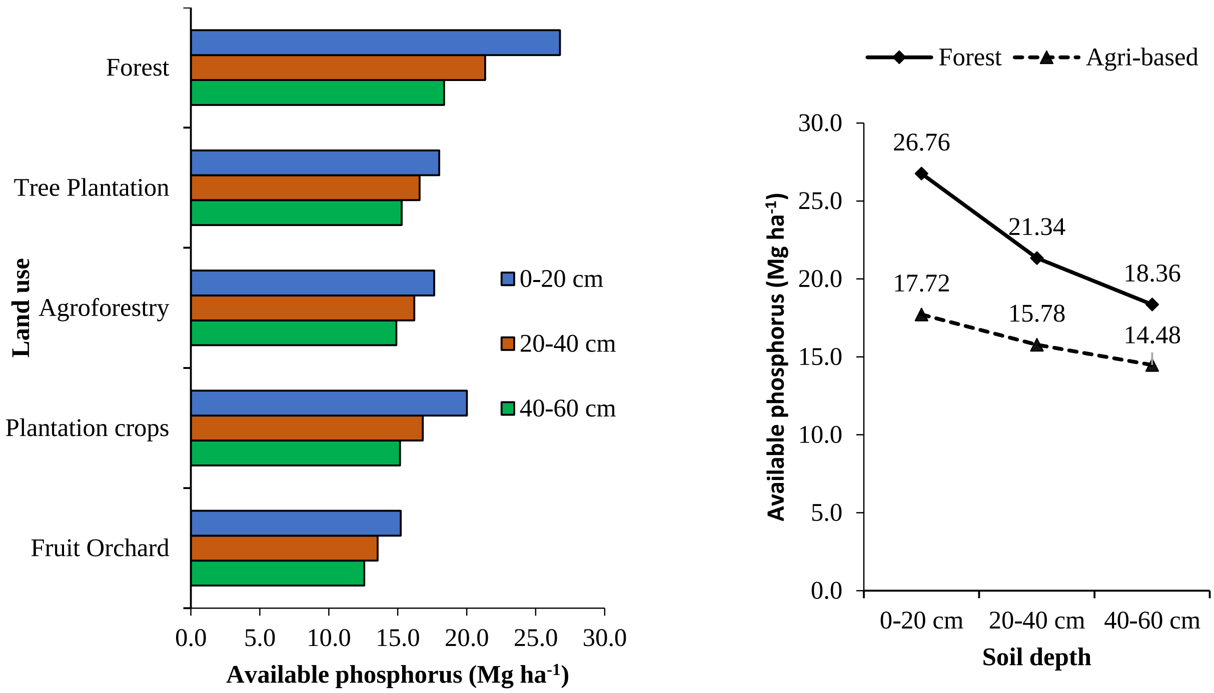


Figure 7. Effect of land uses and soil depth on soil-available phosphorus.

3.3.3. Potassium

The estimated soil-available potassium of the tree-based land use systems is given in Supplementary Table S8 and Figure 8. Land use and soil depth significantly influenced the availability of potassium. The trend of the availability of potassium in the soils of the studied tree-based land use systems was similar to that of the available phosphorus. The highest amount of soil-available potassium was estimated for forests, which was significantly higher than the other tree-based land use systems. The available potassium in forest soils was 41.59% more than the agricultural landscapes. The ordering of tree-based land use system in terms of overall soil potassium availability is forests > commercial crop plantations > agroforestry systems > fruit orchards > forest tree plantations. The amount of these available primary nutrients decreased with the increase in the soil depth for all the land uses. The availability of primary soil nutrients in all the tree-based land use systems was in the order N > K > P. A similar order of these primary nutrients was also reported in earlier studies [20,21,50]. Less soil primary nutrients and organic carbon estimated for tree-based systems than forests can be attributed to the conversions of natural forests and the negative influence of such conversions that were abundantly reported across the globe [26,71].

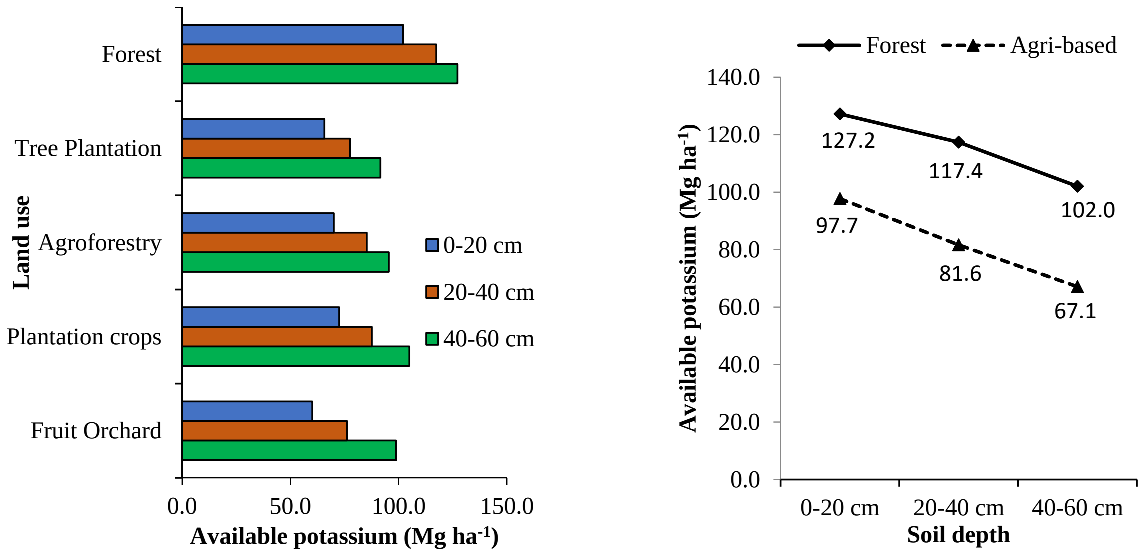


Figure 8. Effect of land uses and soil depth on soil-available potassium.

Additionally, nitrogen, potassium, and phosphorus are differently absorbed and returned to the soil by different tree species growing in the different land use systems due to differences in the soil characteristics [72]. Variations in soil water content, aeration, temperature, microorganisms, and efficiency of the root system to absorb nutrients affect the availability of nutrients in the soil of different land use systems [73]. The availability of primary nutrients in the soil is influenced by the amount of litter produced and the nutrient content in the litter [74]. Litter produces soil organic matter, which is a source of an SOC pool, and the amount of organic matter present in the soil regulates the soil's physical, chemical, and biological properties [65]. Pearson's correlation matrix (Table 2) also confirmed the significant positive correlation of SOC with electrical conductivity, moisture content, and available soil primary nutrients while having a significant negative correlation with soil pH. The quality and quantity of soil organic matter (SOM) in the soil determine the availability of soil nutrients and, thus, the production potential of the soil [66,75,76]. The different tree-based land uses had a different vegetation structure, composition, and production [77], and thus also had a varied nutrient supply [78]. Soil with higher organic matter also has higher total available nitrogen, available phosphorus, and available potassium [58]. Forests have higher organic matter in their soil compared to other land use systems due to diverse vegetation with higher litter production, thus resulting in a higher amount of available nutrients in its soil [20,21,49–51,66]. Organic carbon and nitrogen values are lowest in barren land, intermediate in cultivated well-managed soil, and highest in forest and cultivated unmanaged land [79,80].

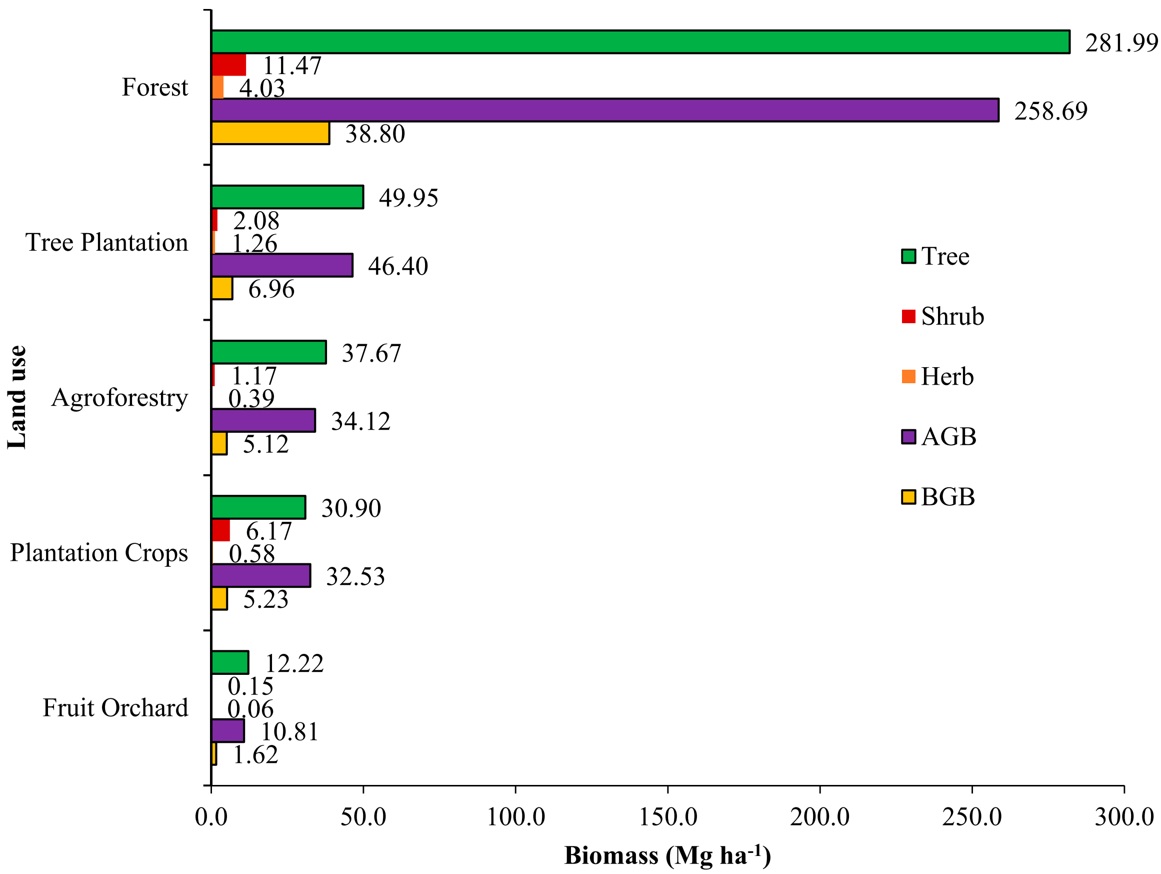
Table 2. Pearson Correlation Matrix showing relationship between soil physical, chemical, and biomass in different ecosystem components.

	EC	pH	MC	SOC	N	P	K	PB	LB
pH	−0.6 **								
MC	0.5 **	−0.4 *							
SOC	0.9 **	−0.4 *	0.5 **						
N	0.7 **	−0.7 **	0.3	0.9 **					
P	0.8 **	−0.6 **	0.6 **	0.9 **	0.7 **				
K	0.5 **	−0.6 **	0.3	0.8 **	0.7 **	0.7 **			
PB	0.7 **	−0.5 **	0.5 **	0.8 **	0.7 **	0.7 **	0.7 **		
LB	0.8 **	−0.7 **	0.4 **	0.9 **	0.8 **	0.7 **	0.7 **	0.7 **	
EC	0.8 **	−0.6 **	0.5 **	0.9 **	0.9 **	0.8 **	0.8 **	0.9 **	0.8 **

MC—moisture content; SOC—soil organic carbon; PB—plant biomass; LB—litter biomass; BC—biomass carbon; ** Significant at the 0.01 level; * Significant at the 0.05 level.

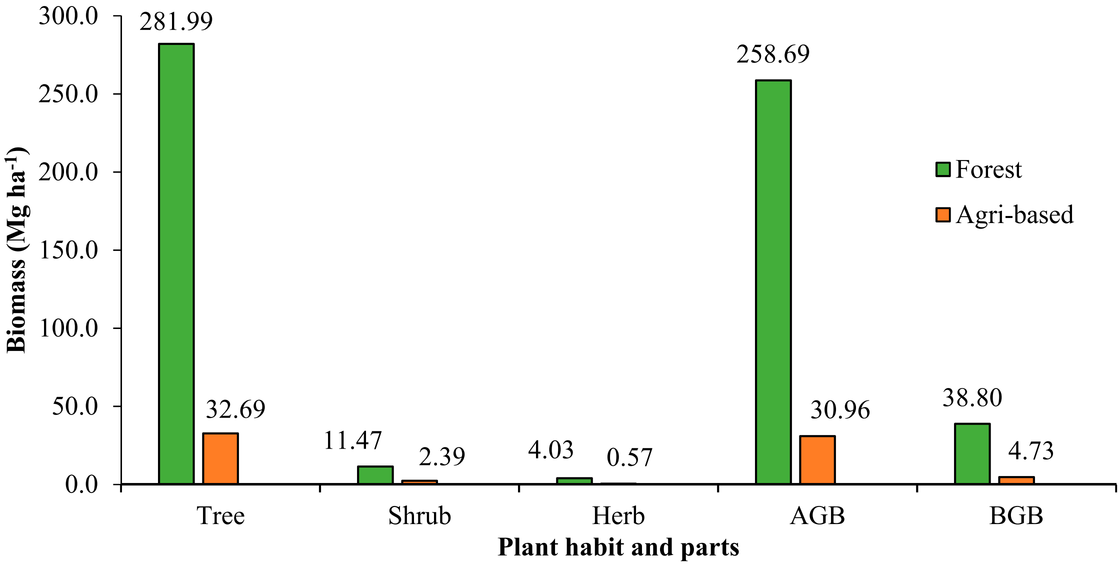
3.4. Biomass Accumulation and Partitioning

Standing plant biomass accumulation and partitioning in different tree-based land use systems of Terai zone of West Bengal are given in Supplementary Table S2 and Figure 9a,b. Biomass stock in the above ground and below ground parts of forests (mixed-species) were the highest with 667.49 and 100.12 Mg ha^{-1}, respectively. High biomass storage in natural forests and stands have been reported from earlier studies [20,81]. The total biomass (trees, shrubs, herbs, and litter) of the forest (mixed-species) was highest (781.21 Mg ha^{-1}) and was followed by the *Shorea robusta* stand (278.69 Mg ha^{-1}), the *Michelia champaca* stand (168.84 Mg ha^{-1}), the *Tectona grandis* stand (163.64 Mg ha^{-1}), the *Lagerstroemia parviflora* stand (159.07 Mg ha^{-1}), the *Anthocephalus cadamba* + *Swietenia macrophylla* plantation (111.86 Mg ha^{-1}), homegardens (97.38 Mg ha^{-1}), the tea plantations (77.07 Mg ha^{-1}), and the least by the *Citrus lemon* orchard (6.28 Mg ha^{-1}). In the agricultural landscape, the highest overall average total biomass was produced by forest tree plantations, agroforestry, commercial crop plantations, and the least by orchards. In all the land use systems, the major contribution was the trees (61.20–99.23%), followed by shrubs, herbs, and litter. Among the forest tree plantations, the plantation of mixed tree species accumulated significantly more biomass than other sole forest tree plantations.



(a)

Figure 9. *Cont.*



(**b**)

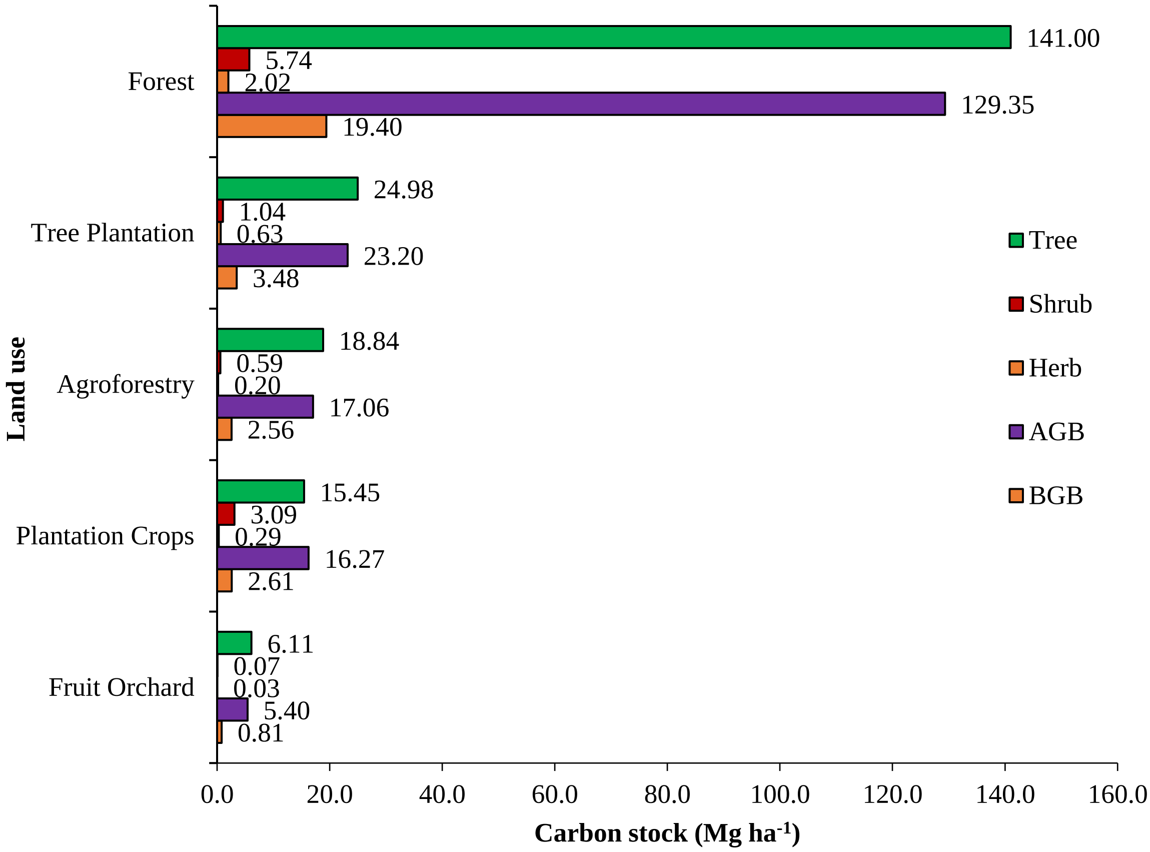
Figure 9. (**a**,**b**). Effect of land uses on plant biomass accumulation.

The amount of biomass estimated in this study for mixed-species forests, pure tree species stands, and homegardens was comparable with earlier studies reported from the Terai zone of West Bengal [20,21,49–52,82,83]. The negligible contributions of understory vegetation to the total biomass of the tree-based land uses were also reported in these earlier studies. A similar biomass accumulation of trees and its allocation to above- and below-ground parts in forest tree plantations, commercial crop plantation, agrisilvicultural plantations, and fruit tree orchards were also abundantly reported [84–88]. Biomass varies with differences in land use systems along with climate, species diversity, stem density, stem size distribution, edaphic conditions, topography site quality, age, density, structure, management practices, and disturbance history, along with variations in canopy height and wood density [22,89,90]. Moreover, it would be inappropriate to draw quantitative comparisons among the studies because of significant differences in sample size, plot size, and dimensions, along with the differences in the environmental conditions and other site factors.

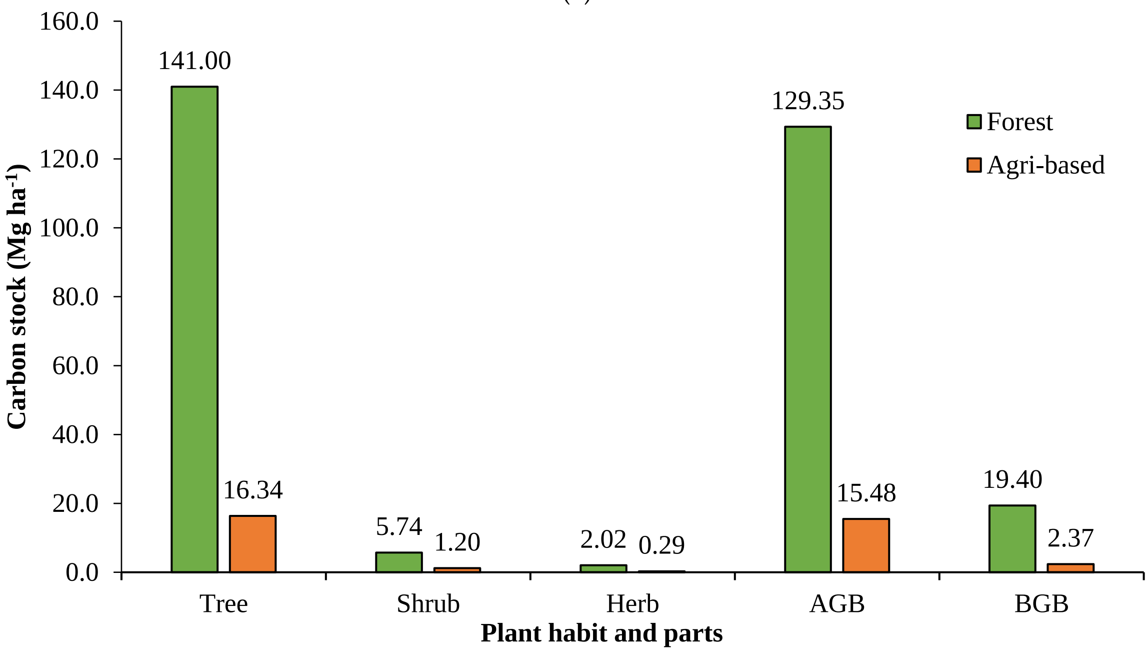
Biomass allocation and partitioning in different tree-based land use systems will be helpful to understand the plant life history strategies [91,92] as it influences the whole-plant net carbon gain and has a direct influence on future plant growth and reproduction [93,94]. This will improve the silvicultural techniques for efficient tree-based land use management along with identification of the productive tree-based land use systems through the productivity of tree species [95]. Biomass accumulation in tree-based land use systems can be conserved as carbon stock and cycling either regionally or globally for planning viable options to mitigate climate change. Quantifying the biomass stored in different tree-based land use systems will help to evaluate the contribution of tree species and their land use systems to net carbon emissions and their potential for carbon sequestration [96].

3.5. Biomass Carbon and Partitioning

The standing plant biomass carbon and its partitioning are significantly influenced by tree-based land use systems (Supplementary Table S9 and Figure 10a,b). The trend is exactly the same as was observed for biomass accumulation because half of the biomass is its carbon [9]. The overall average biomass carbon in the forest was significantly higher than all of the tree-based land use systems in the agricultural landscape. On an overall average, trees, shrubs, and herbs in the forest landscapes stored the highest carbon and were significantly higher than their counterparts in the other tree-based land use systems of the agricultural landscape.



(**a**)



(**b**)

Figure 10. (**a**,**b**). Effect of land uses on plant biomass carbon stock.

Litter biomass carbon was highest in the forest as litter production was highest in it. Above-ground and below-ground biomass carbon was also highest in the forests and, therefore, the total standing live plant biomass carbon in the forest was also highest. Consequently, the overall average total, i.e., live and dead biomass carbon (155.15 Mg ha^{-1}), was also highest in the land use systems of the forest landscapes. In the forested landscapes, the mixed-species forest accumulated the highest amount of biomass carbon 383.81 Mg ha^{-1}, (tree 371.60 + shrub 8.90 + herb 3.31 Mg ha^{-1}), above (333.75 Mg ha^{-1}) and below (50.06 Mg ha^{-1}) ground biomass carbon, litter carbon (6.8 Mg ha^{-1}), and total carbon 390.61 Mg ha^{-1} (biomass + litter). The other best tree-based land use systems in terms of biomass and total carbon were sole tree species stands in forest landscapes (72.49–133.13 and 79.54–139.35 Mg ha^{-1}, respectively) followed by the mixed-species plantation of *Anthocephalus cadamba* + *Swietenia macrophylla* (55.78 and 55.93 Mg ha^{-1}, respectively), homegardens (47.21 and 48.69 Mg ha^{-1}, respectively), a mixed plantation of *Tectona grandis* + *Milvus migrans* (42.12 and 42.99 Mg ha^{-1}, respectively), a *Swietenia macrophylla*-based agroforestry plantation (40.41 and 41.91 Mg ha^{-1}, respectively), tea plantations (38.41 and 38.54 Mg ha^{-1}, respectively), and the least by the *Citrus lemon* orchard (3.1 and 3.14 Mg ha^{-1}, respectively).

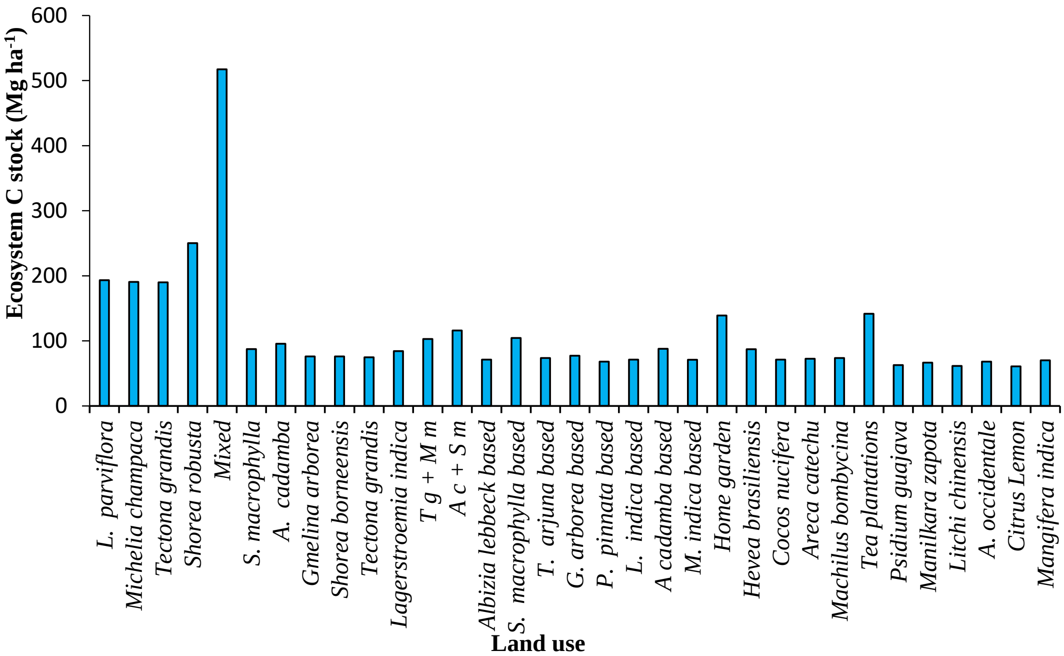
In terms of overall average plant biomass carbon and total carbon stock, the order of the major tree-based land use systems is forest land use (148.75 and 155.15 Mg ha^{-1}, respectively) > forest tree plantations (26.65 and 27.82 Mg ha^{-1}, respectively) > agroforestry plantations (19.74 and 20.14 Mg ha^{-1}, respectively) > commercial crop plantations (18.83 and 19.09 Mg ha^{-1}, respectively) > fruit orchards (6.22 and 6.38 Mg ha^{-1}, respectively). Carbon stock is intricately associated with site quality, nature of land use, choice of species, and other silvicultural practices adopted [97], which explains the higher biomass of forest land uses and hence more carbon stock. Higher biomass of forest land uses was also due to efficient utilization of space due to the presence of grasses/ferns, shrubs, and trees on the same unit area of land. Higher SOC in forest soil increased the rate of plant growth, increasing the biomass again. The tree-based land uses differed in terms of diversity and tree density. It was reported that there exists a potential functional relationship between plant diversity and carbon storage [19–21] which is indicated through the higher carbon storage of mixed-species forests compared to other tree-based land uses. Forest land uses are plant assemblages with high species diversity with more efficient resource use and greater net primary production than with tree-based land uses with one or few species. These plant assemblages sequester carbon with higher rates than those with lower species diversity [98,99].

3.6. Ecosystem Carbon in Tree-Based Land Use Systems

Ecosystem carbon stock was significantly influenced by land use systems (Supplementary Table S10 and Figure 11a–c).

The ecosystem carbon accumulation in the tree-based land uses in both forest and agricultural landscapes was highly variable and was significantly differing among the land uses. As a consequence of the highest total standing plant biomass carbon, litter production, and total SOC of the entire observed soil depth, the forest land uses were also estimated with highest overall average ecosystem carbon stock of 268.24 Mg ha^{-1}. The ordering of forest base land uses in terms of ecosystem carbon accumulation was mixed-species forest > the *Shorea robusta* stand (250.16 Mg ha^{-1}) > the *Lagerstroemia parviflora* stand (193.31 Mg ha^{-1}) > the *Michelia champaca* stand (190.55 Mg ha^{-1}) > the *Tectona grandis* stand (189.93 Mg ha^{-1}). Forest land uses were accumulating 3.24 times more carbon than the land uses in agricultural landscapes. The best tree-based land uses in agricultural landscapes in terms of ecosystem carbon accumulation were the tea plantations (141.74 Mg ha^{-1}) > homegardens (139.02 Mg ha^{-1}) > the mixed plantation of *Anthocephalus cadamba* + *Swietenia macrophylla* (116.02 Mg ha^{-1}) > the *Swietenia macrophylla*-based agroforestry (104.4 Mg ha^{-1}) > the *Tectona grandis* + *Milvus migrans* (102.99 Mg ha^{-1}).

In terms of ecosystem carbon accumulation, the ordering of the major land uses is forests > commercial plantation crop land uses > forest tree plantations > agroforestry land uses > fruit orchards. In forest tree plantations, the best land uses in terms of ecosystem carbon were mixed plantations followed by sole tree species plantations in the order of the *Anthocephalus cadamba* + *Swietenia macrophylla* plantations (116.02 Mg ha^{-1}) > the *Tectona grandis* + *Milvus migrans* plantations 102.99 Mg ha^{-1}) > the *Anthocephalus cadamba* plantations (95.55 Mg ha^{-1}) > the *Swietenia macrophylla* plantations (87.44 Mg ha^{-1}) > the *Lagerstroemia indica* plantations (84.21 Mg ha^{-1}) > the *Shorea borneensis* plantations (76.12 Mg ha^{-1}) > the *Gmelina arborea* plantations (76.07 Mg ha^{-1}) > the *Tectona grandis* plantations (74.70 Mg ha^{-1}). The tree plantations in the agricultural landscape were between 10–15 years of age, dense and unmanaged with no silvicultural operations. This was evidenced from the growth conditions of the plantations, i.e., with less diameter and height, resulting in less biomass and carbon accumulation compared to the forest [21].



(**a**)

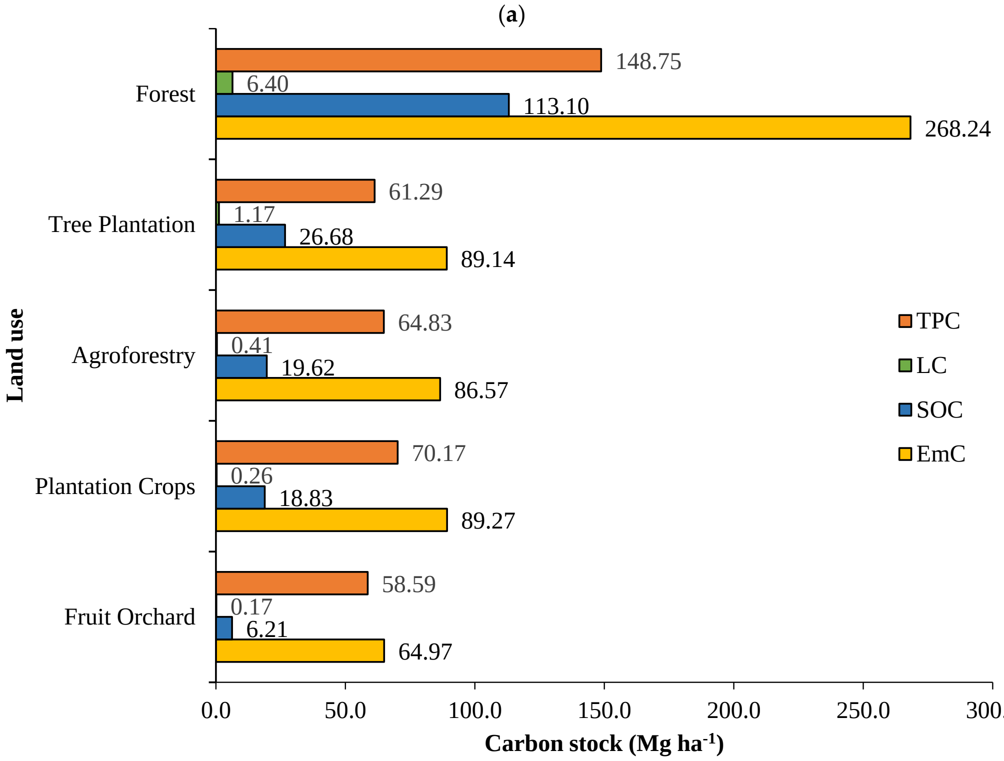


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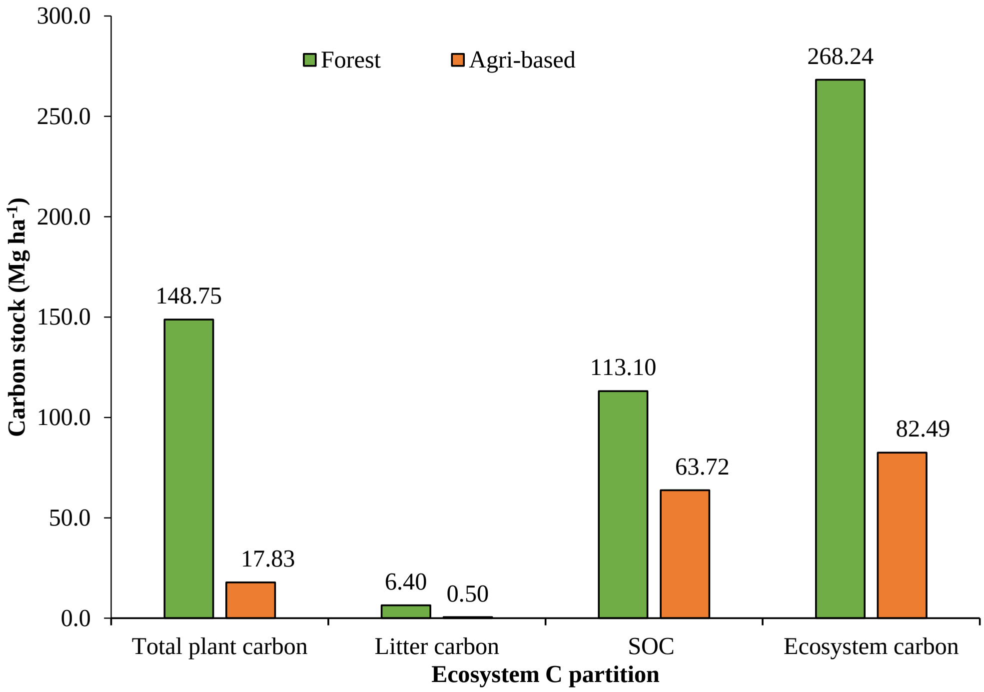
Figure 11. *Cont.*



(**c**)

Figure 11. (**a**–**c**). Effect of land uses on ecosystem carbon stock.

Similarly, in agroforestry land uses, the order based on ecosystem carbon accumulation was homegardens (139.02 Mg ha^{-1}) > the *Swietenia macrophylla*-based (104.40 Mg ha^{-1}) > the *Anthocephalus cadamba*-based (87.90 Mg ha^{-1}) > the *Gmelina arborea*-based (77.31 Mg ha^{-1}) > the *Terminalia arjuna*-based (73.65 Mg ha^{-1}) > the *Albizia lebbeck*-based (71.14 Mg ha^{-1}), the Lagerstroemia *indica*-based (71.14 Mg ha^{-1}) > the *Mangifera indica*-based (71.12 Mg ha^{-1}) > the *Millettia pinnata*-based (68.03 Mg ha^{-1}). Homegardens are prominent in the Terai region of West Bengal, while agrisilvicultural farming is not practiced in the region except for being maintained in the farms of Uttar Banga Krishi Vishwavidyalaya (UBKV), Pundibari, and thus studied with a much smaller sample size compared to forest land uses and homegardens. The age of all the agrisilvicultural systems was about 20–25 years and was intercropped with mainly paddy and winter vegetables. The biomass and carbon accumulations were comparatively much less in the agricultural systems compared to other land uses, which might be due to the smaller sampling size. Further, during the time of observation, the systems were in continuous fallow with some shrubs and herbs as weeds.

In commercial plantation crop land use systems, the order in terms of ecosystem carbon is tea plantations (141.74 Mg ha^{-1}) > the *Hevea brasiliensis* plantation (87.10 Mg ha^{-1}) > the *Machilus bombycina* plantation (73.66 Mg ha^{-1}) > the *Areca catechu* plantation (72.19 Mg ha^{-1}) > *Cocos nucifera* (71.24 Mg ha^{-1}). *Hevea brasiliensis*, *Cocos nucifera*, and *Machilus bombycina* are not commercially viable plantation crops of the region and, thus, are uncommon land uses in the Terai zone of West Bengal. The sampling sizes of these plantations were also much smaller compared to other land uses. Areca nut and tea are commercial crop of the region and, thus, are a prominent land use of the Terai zone of West Bengal. *Psidium guajava*, *Manilkara zapota*, *Litchi chinensis*, *Anacardium occidentale*, *Citrus lemon*, and *Mangifera indica* are also not commercially grown in the Terai region of West Bengal and hence the sample size was small. However, in terms of ecosystem carbon accumulation, these fruit tree land uses are in the order of *Mangifera indica* (70.16 Mg ha^{-1}) > *Anacardium occidentale* (68.18 Mg ha^{-1}) > *Manilkara zapota* (66.48 Mg ha^{-1}) > *Psidium guajava* (62.74 Mg ha^{-1}) > *Litchi chinensis* (61.48 Mg ha^{-1}) > *Citrus lemon* (60.77 Mg ha^{-1}).

Land use management is the major option for sequestering carbon in biomass and soil viably for efficient climate change mitigation by restricting carbon emissions and capturing the atmospheric carbon as permanent storage in tree biomass and soil [100–102]. The best land management for longer-duration carbon storage in soil and biomass is the conversion of less or unproductive and degraded land use through rehabilitation with afforestation by restoring its SOC [103–105], which not only will enhance soil conditions but offset greenhouse gas emissions as well [60]. Land use conversion of inferior or degraded land through afforestation is the best climate change mitigation option because the sequestration rate through afforestation is highest (0.6 Mg C ha^{-1} yr^{-1}) when compared to other mitigation options like conversion to pasture (0.5 Mg C ha^{-1} yr^{-1}), organic amendments (0.5 Mg C ha^{-1} yr^{-1}), residue incorporation (0.35 Mg C ha^{-1} yr^{-1}), no or reduced tillage (0.3 Mg C ha^{-1} yr^{-1}), and 0.2 Mg C ha^{-1} yr^{-1} for crop rotation [102].

The world's forests were reported to be a net source of atmospheric CO_2, primarily due to deforestation and degradation in the tropics [106,107]. Considering the serious issues of climate change, the remaining forests need to be conserved locally, regionally, and globally for their continuous service as the best viable climate change mitigator. However, the forests are required to be supplemented with additional carbon emission offsets through adopting the best available land management option of improving the abundant available degraded land by higher rates of carbon sequestration through afforestation. The reported available degraded land in India was 147 M ha [108]. These land uses urgently need conversion through rehabilitation by afforestation for improving the SOC and biomass carbon stock [20,21,102].

Afforestation programs for the rehabilitation of degraded lands with *Tectona grandis*, *Shorea robusta*, *Michelia champaca*, and *Lagerstroemia parviflora* is recommended as a carbon farming initiative either in the forested landscape or in the agricultural landscape as agroforestry models [20,21,109]. Sole cropping or agroforestry of *Areca catechu*, *Cocos nucifera*, *Machilus bombycine*, *Hevea brasiliensis*, and tree fruit crops can also be tried for carbon farming in the region. Moreover, short rotation tree plantations of *Swietenia macrophylla*, *Anthocephalus cadamba*, *Gmelina arborea*, *Shorea borneensis*, and *Milvus migrans* can be an option to sequester carbon and also to meet increasing industrial and domestic demands [87]. Tea plantations in the region can switch over to organic principles of production but needs suitable research support [47]. Agroforestry systems are ecologically sustainable as they conserves biodiversity and maintain water and soil which improves biotic interactions, buffering changes in temperature and humidity, maintenance of nutrients cycling, efficient use of light, and waste management, determining the wellbeing of people that manage them [64,110–114]. Several reports had indicated improvements in the productivity and creation of carbon sinks after including trees in the agricultural landscapes [115].

Homegardens are prominent landscape feature of the region but need more research and institutional support to make them more remunerative for small landowners [82,83,113,114,116]. Natural resources managed in homegardens improve the conditions of human life and sustain socio-ecological services [117,118]. Homegardens, therefore, as a system, are complementing ecological functions with a household's needs and are now recognized as a potential model for designing socio-ecological sustainable ways of life [119]. Homegardens mimic natural forests in structure and composition [120] and the specific management practices enhance nutrient cycling and increase SOC [121]. Homegardens can enhance SOC as more than half of the carbon assimilated by woody perennials is translocated below ground via root growth and organic matter turnover processes [122]. The available status of nitrogen and organic carbon, along with the optimum soil physical characteristics estimated in the homegardens in the Terai soil of West Bengal, supported the luxurious growth and development of plants, hence carbon being sequestered by the plants and the homegarden soils. This is further supported by the fact that the homegardens with greater biodiversity also ensure the long-term stability of carbon storage in fluctuating environments, apart from augmenting biomass production potential [122]. In addition to sequestering carbon, homegardens can aid in reducing fossil fuel burning by promoting wood fuel production and conserving biodiversity [120]. They can also be instrumental in alleviating pressure from the existing natural forests [122]. The lack of stability or permanence of the carbon sequestered by a land use system is a cause of major concern in carbon sequestration projects currently. Homegardens are permanent tree-based land use systems as their biomass is never completely removed from homegardens and so are resilient [123]. The resilience and stability of the homegardens make them superior to and advantageous over the other tree-based land use systems as biomass can be completely removed from all other tree-based land use systems in the agricultural landscape.

Reports on carbon stocks across the globe indicate that significant amounts of carbon (1.1–2.2 Pg) could be sequestered over the next 30–35 years if agroforestry farming is adopted globally [124]. Agroforestry in general, and in homegardens in particular, thus gains more importance as a carbon sequestration strategy because of the carbon storage potential in its multiple plant species and soil, as well as its applicability in agricultural lands and in reforestation [64,123]. This clearly advocates agroforestry as small landholders' land use systems in the tropics as a viable and low-cost climate change mitigation option [123]. Intensive industrialized systems have failed in sustainable issues, as their achievements were laced with high environmental costs like climate change [125]. Therefore, the remedy is searching for a new paradigm of climate-smart farming systems for sustainable food security and carbon farming. The option best suited was improving the capacities of the traditional systems like agroforestry and homegardens [126]. These traditional systems have the potential to maintain optimum productivity without losing the diversity of components and functions, while farming carbon as well [125].

The diminishing terrestrial carbon sink [18,64,127] has led to the recognition of terrestrial ecosystems in mitigating climate change globally [128,129]. The results of the present study clearly indicate that land use and land cover change (LUCC) are crucial for the distribution, magnitude, and mechanisms of terrestrial carbon sources and sinks locally and globally [128]. However, the regional patterns, magnitude, and driving mechanisms of terrestrial carbon sinks and sources are uncertain and vary across regions [128,130]. It was reported that LUCC contributes to the uncertainties in estimating the carbon fluxes in and out of the terrestrial ecosystems [131–134]. The present study also did not estimate the carbon fluxes in and out of the systems due to the absence of detailed LUCC databases of the study region [135–138]. Carbon exchange between these tree-based land use systems and the atmosphere would have generated a more accurate estimation of the carbon budgets of the Terai region of West Bengal to efficiently support policy and management decisions for climate change mitigation [139–142]. It is thus recommended, based on the results obtained from the present study, that it is necessary to include detailed dynamics of land use change while estimating the LUCC carbon at any spatial level [137]. Otherwise, it is impossible to accurately quantify the geographic distributions, magnitudes, and mechanisms of terrestrial carbon sequestration at the local to global scales. Land management through tree-based carbon farming can mitigate climate change in the true sense as it is an avoided emission [143] and transfers net carbon from the atmosphere to the land as well [103]. Tree-based land use management was a viable objective set in ambitious 4 per mille global initiative [101,102]. This is because afforestation has the potential to sequester the highest SOC as evidenced globally [94] and, thus, constitutes "true" sequestration [103].

4. Conclusions

It was evidenced that forests had the highest SOC stock with the lowest pH, higher EC and soil moisture content, and the highest availability of primary soil nutrients. Regarding ecosystem carbon accumulation, the sequence of the land uses was forests > commercial crop plantations > forest tree plantations > agroforestry > fruit orchards. Overall, the forests accumulated 3.24 times more carbon than the other tree-based land uses in agricultural landscapes. The results of the present study also indicated that land use and land cover change (LUCC) are crucial determinants for terrestrial carbon sources and sink in the region. Considering the significant differences between the SOC and the standing tree biomass among the trees-based land use systems in the Terai zone of West Bengal, it is recommended to conserve the remaining natural forests, as their conversion will cause significant emission losses of terrestrial carbon. Additionally, afforestation programs for rehabilitating degraded lands with *Tectona grandis*, *Shorea robusta*, *Michelia champaca*, and *Lagerstroemia parviflora* are recommended as carbon farming initiatives on the degraded forested landscape or the agricultural landscape. Homegardens are a prominent landscape feature of the region but need more research and institutional support to make them more remunerative for small landowners. The results obtained from the present study can be used in future research for a detailed study of ecosystem carbon dynamics along LUCC at any spatial level. The regional patterns, magnitudes, and driving mechanisms of terrestrial carbon sinks and sources are uncertain and vary across the regions. Land use and land cover change (LUCC) cause uncertainties in estimating the carbon fluxes in and out of terrestrial ecosystems. Therefore, carbon exchange between the land use systems and the atmosphere must be studied to estimate carbon budgets accurately. The detailed dynamics of land use change need to be studied while estimating the LUCC carbon to accurately quantify the geographic distributions, magnitudes, and mechanisms of terrestrial carbon sequestration at the local to global scales.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land12061155/s1. Table S1. Effect of tree-based land-use systems on SOC (Mg ha^{-1}) at different soil depths; Table S2. Effect of tree-based land-use systems on biomass accumulation and partitioning (Mg ha^{-1}); Table S3. Effect of tree-based land-use systems on soil EC (dS m^{-1}) at different depths; Table S4. Effect of tree-based land-use systems on soil pH at different depths; Table S5. Effect of tree-based land-use systems on soil moisture (%) at different depths; Table S6. Effect of tree-based land-use systems on soil available nitrogen (kg ha^{-1}) at different depths; Table S7. Effect of tree-based land-use systems on soil available phosphorus (kg ha^{-1}) at different depths; Table S8. Effect of tree-based land-use systems on soil available potassium (Kg ha^{-1}) at different depths; Table S9. Effect of tree-based land-use systems on biomass carbon stock and partitioning (Mg ha^{-1}); Table S10. Effect of tree-based land-use system on ecosystem carbon (Mg ha^{-1}).

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