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Stand Structure, Biomass and Carbon Storage in *Gmelina arborea* Plantation at Agricultural Landscape in Foothills of Eastern Himalayas

Mendup Tamang [1], Roman Chettri [1], Vineeta [1], Gopal Shukla [1], Jahangeer A. Bhat [2], Amit Kumar [3,*], Munesh Kumar [4], Arpit Suryawanshi [5], Marina Cabral-Pinto [6] and Sumit Chakravarty [1]

1 Department of Forestry, Uttar Banga Krishi Viswavidyalaya, Pundibari, Cooch Behar, West Bengal 736165, India; dupmentamang99@gmail.com (M.T.); romanchettri18@gmail.com (R.C.); vineeta@ubkv.ac.in (V.); gopal@ubkv.ac.in (G.S.); sumit@ubkv.ac.in (S.C.)
2 Department of Forest Products and Utilization, College of Horticulture and Forestry, Rani Lakshmi Bai Central Agricultural University, Jhansi 284003, India; jahan191@gmail.com
3 School of Hydrology and Water Resources, Nanjing University of Information Science and Technology, Nanjing 210044, China
4 Department of Forestry and Natural Resources, H.N.B. Garhwal University (A Central University), Srinagar Garhwal, Uttarakhand 249161, India; muneshmzu@yahoo.com
5 Department of Soil Science and Agricultural Chemistry, College of Agriculture, Rani Lakshmi Bai Central Agricultural University, Jhansi 284003, India; arpitsurya226@gmail.com
6 Department of Geosciences, University of Aveiro, Campus de Santiago, 3810-193 Aveiro, Portugal; marinacp@ua.pt
* Correspondence: amitkdah@nuist.edu.cn

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Abstract: In the modern era, *Gmelina arborea* plantations are a hotspot of future research because of their high carbon sequestration potential. The present work was conducted during 2018 to 2020 on a young unmanaged *Gmelina* farm to understand the ecosystem's carbon and its dynamics. The study area was categorized into three age classes: ≤5, 5–10, and 10–15 years. In a plantation, *Gmelina* trees (10%) were randomly selected while other trees (90%) were also taken into the consideration for ecosystem carbon. A stratified random nested quadrate sampling method was adopted for analyzing other vegetation forms under study. Overall, 51 individual species in the studied *Gmelina* farm were found which includes 23 tree species, 7 shrub species, 16 herbs, 2 climbers, and 3 species of ferns. The estimated quantitative vegetation parameters and diversity indices indicate that the plant assemblages were heterogeneous with native diverse species evenly distributed with fairly higher densities, frequencies, and abundance. Herbs were the most important species followed by shrubs and trees. Consequently, with the increasing age of plantation, the richness of plant species increased. Soil properties were significantly influenced by the age of the plantation but exhibited no discreet trend. Total biomass density and total carbon density increased with increasing plantation age while no drastic variation was found in available soil organic carbon (SOC) because of insignificant variability in litter production. Total carbon, available SOC (up to 60 cm depth) and ecosystem carbon in the three age class plantations fell in the ranges of 54.51–59.91, 48.18–55.73, and 104.81–110.77 Mg ha^{-1}, respectively. The carbon sequestration potential of *Gmelina arborea* is higher compared to other reported species and highly supportive of converting unutilized agricultural landscapes to reduce the atmospheric carbon dioxide in future.

Keywords: plantation; climate change; land use management; carbon sequestration; soil

1. Introduction

Climate change is a global concern and forests play a vital role in regulation as they are a viable option for offsetting terrestrial carbon dioxide emissions [1,2]. Unfortunately, forests alone are not enough to offset all the terrestrial emissions [3] and there is a need is to find an alternate viable option to bridge this gap [4]. The accepted viable alternative is trees outside forest (TOFs) in both agricultural and human-dominated landscapes, which will not only meet timber, industrial, and livelihood demands but also effectively and viably facilitate offsetting carbon dioxide (CO_2) emissions with the forest ecosystems [5]. Tree-based land use systems including those in the nonforested landscapes such as agricultural land play an important role in global carbon (C) cycling since these are one of the largest C pools which act as a potential C sink and also as one of the major sources of CO_2 [4]. The productivity of the plantations is higher (3.2 Mg ha^{-1} yr^{-1}) than the productivity of natural forests (1.1 Mg ha^{-1} yr^{-1}) [6]. This is because plantation forestry has an added advantage over the natural forest in terms of better silvicultural practices [7]. Thus, the past decades have witnessed increased interest in tree plantations in both agricultural- and non-agricultural-dominated landscapes in the country, especially Teak (*Tectona grandis*), *Gmelina* (*Gmelina arborea*), Deccan Neem (*Melia azadirach*), Champa (*Michelia champaca*), and Sal (*Shorea robusta*) among the farmers and entrepreneurs, particularly in the sub-Himalayan, i.e., Terai, region of West Bengal [8]. *Gmelina arborea*, which is native to India and a prime fast growing species in farm forests in India, has the potential to replace and act as a substitute for exotic timbers in the country [9]. The species has the potential to store C and is also remunerative due to its multiple uses [8,10]. In addition to timber, wood of the tree is used for fuel wood, paper and pulp making, and is used in other forest-based industries [8].

Gmelina plantations have been established and encouraged in small woodlots, home gardens, and agroforestry settings in the tropics and subtropics [8], including the Terai region of West Bengal. The potential of these trees to offset C emission needs to be assessed and monitored properly for which local, regional or national inventories are required [4]. Understanding the diverse and complex tree-based land use systems for C sequestration and nutrient cycling has become a global research interest [11]. The United Nations Framework Convention on Climate Change (UNFCCC) has recognized the importance of plantation forests as a greenhouse gas (GHG) mitigation option, as well as the need to monitor, preserve and enhance terrestrial C stocks [12]. Studies on associated plant species biodiversity, quantification of biomass, and C are available for *Gmelina* farms in India but few attempts have been made regarding chronosequencing of C sequestration potential of these plantations along with associated plant biodiversity [8], while none have been carried out for the Terai region of West Bengal. The study was thus attempted with the hypothesis that there will be chronosequence variations in terms of diversity, biomass, carbon storage, and soil properties of the unmanaged *Gmelina* farm in Terai region of West Bengal with the following objectives: (i) to assess physio-chemical characteristics of soil and (ii) to assess phyto-diversity, biomass, and carbon storage of the *Gmelina* farm. The present study was the first attempt in the region to assess the potential of *Gmelina* farms, which will be helpful in the conversion of the unutilized land for C farming to create additional C sinks and may further assist in trapping the available carbon dioxide in the atmosphere.

2. Materials and Methods

2.1. Site Description

The present study was conducted in the Terai region of West Bengal at Cooch Behar district from September 2018 to February 2020. The study site is a sub-Himalayan region located between 26°30′–26°56′ N latitude and 88°7′–89°53′ E longitude. The area around (within 10 km) the University (Uttar Banga Krishi Viswavidyalaya, Pundibari—UBKV) campus was surveyed for sampling plantations of *Gmelina* in the agricultural landscape which was a predominantly rice-based cropping system with potato and/or fallow. Moreover, the cropping system is not intensive in the area and the land of most of the farmers was marginal; therefore, they have poor resources. *Gmelina* or any other tree plantations were not normally planted as a block in crop land by the farmers in the Terai region except some scattered plantations mostly in home gardens or as boundary or roadside plantations. The plantations were generally developed on land normally unsuitable for annual cropping by farmers and nonfarmers, in addition to crop land of the owners, and were kept fallow until the planting of *Gmelina* or any other tree plantations. These plantation owners were normally absentee growers. *Gmelina* was densely planted with a squared geometry of 3 × 3 m. The plantations were normally kept aside undisturbed without replanting the gaps and allowing spontaneous plant growth. The area of most of the plantations was at least one acre.

2.2. Climate and Weather

The study area is under moist tropical conditions [13], where average minimum and maximum temperatures varied from 22.8 (during winter, January) to 32.32 °C (during September). On average, the annual rainfall varied from 2000 to 3500 mm, the bulk of which occurred during the premonsoon and monsoon periods—i.e., from May to September. The relative humidity (RH) varied from 55 to 90%. The study area is warm and humid except with a sort of spell of winter from December to March (Supplementary Figure S1).

2.3. Sampling and Inventory

As there were only 21 plantations in the study area, we were able to include them all in the study. The selected plantations were marked using GPS (Model Garmin 72) and based on their availability, plantations of three age classes (seven plantations each) were categorized—i.e., ≤5 (Age class I (AC I)), 5–10 (AC II) and 10–15 years (AC III; Supplementary Table S1). Each selected plantation was of about one acre in area. At each plantation, the outer rows were excluded from measurement as a buffer. From the interior rows, all Gmelina stems with diameters at breast height (dbh) of more than 10 cm were recorded and additionally 10% of these trees were selected randomly and their heights were recorded. Species other than *Gmelina*—all trees with a dbh > 10 cm—were recorded along with their tree heights. Similarly, other tree species with dbhs ≥ 10 cm in the plantation were also selected. Shrubs and herbs were sampled following a stratified random nested method, where three (5 × 5 m) quadrats were marked diagonally across the plantation (two at the corners and one at the center) for shrubs, while for herbs five 1 × 1 m plots were marked at all corners and one at the center of the plantation. Most of the plant species were identified in the field itself, while those which could not be identified were preserved by mounting in herbarium sheets following standard procedures for identification. The mounted specimens were cross-checked with the available herbarium in the Department of Forestry UBKV Pundibari, West Bengal. A full inventory of the plant species found at the plantations was prepared including trees, shrubs, and herbs. The biomass of plantations was separately estimated for trees, shrubs, and herbs. Tree biomass was estimated separately for all the species. Litter samples were collected once during January from ten sampling locations with plots size of 1 × 1 m distributed throughout the plantation. To estimate the plantation soil properties, a total of 63 representative soil samples were collected from each plantation site—i.e., ≤ 5 (AC I), 5–10 (AC II) and 10–15 years (AC III) at three different depths (0–20, 20–40, and 40–60) using Dutch augur. Prior to estimation, collected soil samples were air-dried, grinded with a wooden pestle, passed through a 2 mm sieve, and stored in cloth bags for further analysis.

2.4. Quantitative Parameters

For each plantation, individual species were recorded for quantitative parameters following standard procedures. Importance value index (IVI) as a summation of relative frequency (RF), relative density (RD), and relative abundance (RA), as suggested by Cintron and Novelli [14], was estimated to analyze the sociability of the plant assemblages in the plantations.

2.5. Species Diversity Indices

Various diversity indices were estimated to analyze plant diversity of the plantations. Species richness was described by the available species number in a studied plantation.

Menhinick's index (D′) [15] is based on the total number of species and the total number of individuals of all species (N). D′: = S/ $\sqrt{N}$. This index, unlike the Shannon–Wiener index, gives more weightage to the rare species. The concentration of dominance was used to evaluate species dominance within a community [16]. This provides information on number of times a particular species was encountered during the sampling. Higher values are indicative of less diverse community and concentration of dominance is calculated using the following formula:

$$C = \sum (n_i / N)^2 \quad (1)$$

where n_i denotes the number of individuals of a species

The Shannon–Wiener diversity index (H′) [17] of species diversity was used to describe diversity, where higher values suggest more diverse nature of the plantations. The index was estimated using following formula:

$$H' = -\sum (n_i / N) \ln (n_i / N) \quad (2)$$

The method of Pielou [18] was used to estimate the species evenness index:

$$EI = H' / \ln N. \quad (3)$$

2.6. Biomass and Carbon Stock Estimation

A nondestructive method was adopted for quantifying above-ground biomass (AGB) of the trees using a recent allometric model developed for forest types in northeast India [19].

$$AGB = 0.18D^{2.16} \times 1.32 \quad (4)$$

where D is the diameter of tree at breast height.

Below-ground biomass (BGB) was estimated as 15% of the AGB [20]. Total tree biomass was the summation of AGB and BGB, which was estimated for each tree in the sampled area and then summed up. The total herbs, shrubs, and tree biomass was further converted into carbon by multiplying a factor of 0.50 [20].

2.7. Soil Properties

Soil properties such as bulk density (core sampler method), moisture (volumetric method), electrical conductivity or electrical conductivity (EC) (soil water suspension method), pH (Beckman's pH meter), soil organic carbon (Walkley and Black's rapid titration method), available nitrogen (Modified Kjeldahl method), available phosphorus (Bray's method) and available potassium (Flame Photometer method) were analyzed following standard methods [21–23]. Soil organic carbon (SOC) stock was estimated by multiplying the SOC with weight of the soil (bulk density and depth) and is expressed as mega grams per hectare (Mg ha^{-1}) [24].

2.8. Statistical Analysis

The data were analyzed using the software package Gen Stat Eleventh Edition (VSN International, Oxford, UK). One-way analysis and a Duncan multiple range test (DMRT) test were also employed.

3. Results and Discussion

3.1. Diversity Indices and Species Composition

The diversity indices of *Gmelina* farm are given in Table 1. Overall, we found 51 species including 23 tree species, 7 shrub species, 16 herbs, 2 climbers and 3 species of ferns. Four species were not identified (see Supplementary Tables S2–S5).

Table 1. Diversity indices of *Gmelina* farm forestry plantations.

Parameters	Overall	Age Classes (Year)		
		≤5	5–10	10–15
Species richness	51	35	37	43
Genera richness	46	35	35	42
Family richness	33	25	25	30
Species diversity index	1.18	0.54	0.62	0.59
Concentration of dominance	0.03	0.04	0.05	0.04
Shannon–Wiener index	1.29	1.54	1.59	2.00
Evenness index	8.69	3.35	3.92	3.65

Amongst the plant species found to be associated with *Gmelina* plantations of all age classes, herbs were prominently found followed by trees, ferns and climbers. Similar studies on associated plant species diversity in tree plantations in agricultural landscapes have been previously reported with either shrubs or herbs dominating [25]. Dominance of one stratum generally suppresses the diversity of another [26].

The different diversity indices estimated for different age class plantations are given in Table 1. Overall, the plant assemblages in the plantations were more diverse, evenly distributed, heterogeneous, and stable compared to the different age class plantations. The concentration of dominance of the different age classes estimated separately was much less but indicated a similar and higher probability of a species being encountered during sampling in these plantations. The H' index reflects structure and heterogeneity of plant assemblages in an ecosystem—i.e., higher the index value, the more diverse and stable the community is [27]. The index values estimated for the different age class plantations were much less but increased with increasing plantation age—i.e., the plantations with increasing age became more heterogeneous and stable. Species in the different age class plantations were more or less evenly distributed.

This is a considerably higher diversity of associated plant communities developed in the *Gmelina* farm as there were no disturbances. The plantations were not managed silviculturally by the owners after planting as they were kept aside. A similar increase in plant diversity was also reported for farm forestry plantations and other nonforested landscapes when they were not managed or kept aside [28]. The diversity of the associated species in the *Gmelina* plantations increased with the increasing plantation age, reflecting the compatibility of the associated species with *Gmelina*, which is in contrast to the studies reporting on teak plantation due to its allelopathic effect [25]. Moreover, canopy gaps in the plantation allowed enough sunlight to favor understory growth for early successional species [29]. The undisturbed *Gmelina* farm forestry plantations in the Terai zone of West plantations aided the rehabilitation of fallow crop land in an agricultural landscape, allowing homeostatic capability of the system [30].

The studied *Gmelina* undisturbed farm forestry plantations with increasing age promoted succession along with resetting of many ecosystem processes such as improving microclimate, soil fertility through litter input, microbial diversity and activity, biomass production, and sequestration capacity [31]. Studies have confirmed succession in sole tree species plantation resetting the disrupted processes associated with diversity [32]. Species richness listed in the plant assemblages of the *Gmelina* plantations was comparable with an earlier study involving plantations of *Tectona grandis*, *Shorea robusta*, *Michelia champaca*, and *Lagerstroemia speciosa*, but less so than miscellaneous species stands in the Chilapatta Reserve Forest not more than 10 km from the present study sites [33].

Generally, tree plantations outside the forest were recolonized with forest species of the regional species pool [34], which promotes rehabilitation because of improved site quality factors suitable for growth of native species [31]. It was shown in all the earlier studies that in absence of disturbance, structural homogeneity of the plantation with succession gradually leads to heterogeneous multilayered secondary forests with more heliophytes and sciophytes in the understory. In the present study, 51 plant species including trees, shrubs, herbs, climbers, and ferns were documented from the *Gmelina* farm and if left to grow undisturbed until their natural rotation, a more heterogeneous secondary forest can be expected in this agricultural landscape. Rehabilitation of landscapes is a time-consuming process which needs at least as long as 100 years to reset back, akin to the earlier native forest [35] but not the same in terms of species richness and structure [25]. This study, along with previous studies, supports the policy of using tree planting to restore degraded agricultural landscapes particularly unsuitable for annual cropping with tree plantations of *Gmelina* or other timber species for biodiversity, ecosystem functions, sustainable forestry, and ecosystem services [25].

3.2. Vegetation Analysis

Frequency, abundance, density, and IVI estimated for the plantations are provided in Supplementary Tables S2–S5. In central and eastern Himalayan forests, frequency of tree layer was reported with a range of 10–100%, shrub layer 10–80%, herb layer 10–100% [27,36,37]. A similar frequency range was also observed for the species in the present study. The species documented in the study sites were native species of the region and were mostly used by the local people for food, medicine, and fodder [38,39]. Frequency or the degree of distribution of the species indicates the chance of occurrence of a species while sampling. *Acacia auriculiformis*, *Albizia lebbeck* and 15 other species had lowest representations in the sampled plots, while *Ageratum houstonianum* had the highest representation. Correspondingly, these species were also observed with the lowest and highest relative representations, respectively, while sampling. Generally, the representation of species and their relative representations during sampling initially increased—i.e., from AC I to AC II—but then decreased from AC II to AC III.

Higher chance of occurrence of the associated plant species in *Gmelina* farm forestry plantations also generally increased the numerical strength and abundance of the species, which resulted in the easier establishment of these species in the plantations. These species were initial colonizers as they adapted well as understory strata in the *Gmelina* farm forestry plantations. *Dalbergia sissoo*, *Lagerstroemia speciosa*, *Albizia lebbeck*, *Acacia auriculiformis,* and *Moringa oleifera* (all trees) were estimated as having the lowest densities, while *Clerodendron infortunatum*, a shrub with the highest density in the plantations amongst the associated species. Species density varies with forest community type, forest age class, tree species, size class, site history, site quality factors, and disturbance [40]. *Acacia auriculiformis*, *Albizia lebbeck*, *Dalbergia sissoo*, *Lagerstroemia speciosa*, and *Moringa oleifera* were the least abundant, while *Clerodendron infortunatum*, a shrub, was the most abundant associated species in the plantations.

Based on estimated IVI values, the most important of all the species associated with *Gmelina* plantations was *Clerodendron infortunatum*, a shrub, and the least were *Acacia auriculiformis*, *Albizia lebbeck*, *Dalbergia sissoo*, *Lagerstroemia speciosa,* and *Moringa oleifera*. The other important associated species in the plantations were *Clerodendron infortunatum*, *Ageratum houstonianum*, *Cynodon dactylon*, *Ageratum conyzoides*, *Lantana camara*, *Diplazium esculentum*, *Fragaria vesca*, *Lucas aspera*, *Tabernaemontana divaricata*, *Mikania micrantha*, *Colocasia esculenta*, *Pouzolzia zeylanica*, *Bombax ceiba*, *Paspalum distichum*, *Matteuccia struthiopteris,* and *Oxalis corniculata* (see Supplementary Tables S2–S5). Based on the higher IVI values of these species as compared to other recorded species, it can be concluded that these species were successful primary colonizers in the *Gmelina* farm forestry plantations, forming a definite structure with vertical understory strata comprising trees, shrubs, and herbs [30].

3.3. Soil Moisture, pH, Electrical Conductivity and Bulk Density

Soil moisture and EC (Table 2; Supplementary Tables S6 and S7) decreased gradually with increase in soil depth from 0–20 cm to 40–60 cm in plantations of all age class series but soil pH (Table 2; Supplementary Table S7) exhibited a reverse trend, while soil bulk density (Table 2) exhibited no trend with depth. None of these soil physical parameters show any consistent trend with increased plantation age, which is also evidenced by the staggered relationship observed between plantations of different age classes and their soil physical parameters (Table 3). This indicates that the soil of *Gmelina* plantations was highly inconstant and had unstable characteristics as these were planted in agricultural landscapes [41–43].

Table 2. Soil moisture, pH, electrical conductivity (EC) and bulk density in *Gmelina* plantations.

AC	Moisture (%)			pH			EC (m mhos cm^{-1})			Bulk Density (g cm^{-3})		
	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3
I	28.23	24.56	21.22	5.56	6.19	6.59	0.31	0.29	0.17	1.73	1.66	1.56
II	26.94	23.36	21.01	5.28	5.65	6.24	0.25	0.16	0.09	1.54	1.62	1.55
III	29.59	25.84	22.93	5.39	5.81	6.27	0.28	0.20	0.17	1.53	1.58	1.63
Mean	**28.25**	**24.59**	**21.72**	**5.42**	**5.88**	**6.37**	**0.28**	**0.22**	**0.14**	**1.6**	**1.62**	**1.58**
S_{em}	**1.10**	**1.15**	**1.02**	**0.22**	**0.21**	**0.19**	**0.05**	**0.05**	**0.05**	**0.65**	**0.23**	**0.25**
CD	**3.38**	**3.54**	**3.13**	**0.66**	**0.65**	**0.59**	**0.15**	**0.17**	**0.15**	**NS**	**NS**	**NS**

AC I (Age class I—≤5 years); AC II (5–10 years); AC III (10–15 years); D1—soil depth 0–20 cm; D2—20–40 cm; D3—40–60 cm; Sem—standard error mean; CD—Critical difference.

Table 3. Pearson correlation matrix of stand, soil properties Total Biomass Density (TBD) and TCD.

	AC	pH	EC	N	P	K	SOC	TBD
AC	1							
pH	−0.266 *	1						
EC	−0.120	0.616 **	1					
N	0.060	−0.445 **	−0.170	1				
P	−0.077	−0.072	−0.142	0.002	1			
K	0.253	−0.045	−0.018	0.063	0.020	1		
SOC	−0.051	0.043	0.382 **	−0.121	−0.120	−0.043	1	
TBD	0.795 **	−0.128	−0.009	0.025	−0.135	−0.107	−0.067	1

** Significant at 0.01 level; * Significant at 0.05 level (2 tailed); AC—age class; EC—electrical conductivity; N—nitrogen; P—phosphorus; K—potassium; SOC—soil organic carbon; TBD—Total Biomass Density (total biomass having both ABG and BGB).

Prior to the establishment of plantations, lands were unused or were agricultural fallow in and around crop lands. The plantations were not at all managed except during planting with farmyard manure (FYM) application or at the most once after one year of planting. All these soil physical parameters except bulk density were significantly influenced by the age of the plantations which, however, did not exhibit any discreet trend with increasing age of the plantations. Soil water holding capacity (WHC) in tree-based land use systems is influenced by rainfall, temperature, humidity, amount of incident radiation on the soil floor, structure, and function of plant cover [44]. The Terai region of West Bengal located in the foothills of eastern Himalayas has a tropical moist climate with high rainfall and acidic soil [45]. High humidity and rainfall (Supplementary Figure S1) increased the soil water retention by reducing evaporation rates and increasing the infiltration of water [33]. Moreover, tree-based land use systems were reported with higher soil organic matter on the surface soil layer due to litter input increasing the EC, thus making the soil more acidic and these soils can also absorb and hold substantial quantities of water as compared to subsurface layers [38]. Higher acidity of surface soil is due to accumulation and subsequent slow decomposition of organic matter releasing acids [46]. Lower pH at soil surface inactivates the soil fauna resulting in slower humus decomposition with more nondecomposed matter on the soil floor [47]. The undisturbed *Gmelina* plantations increased the soil organic matter continuously without being removed, which efficiently regulated the soil physical properties by increasing leaching of bases and weathering process due to decomposition of litter [48].

Soil moisture, pH, and EC in the plantations of different age classes (AC I—≤ 5 years, AC II—5–10 years, and AC III—10–15 years) varied significantly because of site quality factors at the landscape level (Supplementary Tables S6 and S7) arising due to microlandscape differences resulting from differences in developing understory vegetation and gaps in the *Gmelina* canopy. There was mortality of *Gmelina* after its planting which resulted in its discontinuous canopy. Differences in the development of understory vegetation in the *Gmelina* plantations are indicated from the differences in its community parameters. The skewed variability in soil properties in the plantations of different age classes was due to no silvicultural operations performed and was thus strongly influenced by socio-ecological conditions [49] such as vegetation structure of the plantations as well as interculture operations performed on surrounding crop land [50].

3.4. Soil Available Organic Carbon, Nitrogen, Potassium and Phosphorus

The amount of available SOC, N, P, and K decreased with increasing soil depth, highest at surface layer and lowest in the deepest layer analyzed (Table 4; Supplementary Tables S8–S11).

Table 4. Soil organic carbon and available nitrogen, phosphorus and potassium.

AC.	SOC (Mgha^{-1})			Available N (Kg ha^{-1})			Available P (Kg ha^{-1})			Available K (Kg ha^{-1})		
	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3
I	25.64	18.74	11.35	157.1	93.63	60.78	14.63	15.08	14.88	65.11	57.34	54.36
II	22.15	14.75	11.28	172.0	126.8	73.62	14.15	13.23	11.84	86.37	71.68	72.28
III	22.11	15.57	13.18	141.7	108.7	73.42	14.76	16.76	13.76	86.98	78.58	71.20
Mean	**23.3**	**16.35**	**11.94**	**156.9**	**109.7**	**69.27**	**14.51**	**15.02**	**13.49**	**79.49**	**69.2**	**65.95**
S_{em}	**1.87**	**1.46**	**0.58**	**15.45**	**17.60**	**16.39**	**0.92**	**1.93**	**0.89**	**8.30**	**10.14**	**9.79**
CD	**5.77**	**4.50**	**1.79**	**47.59**	**54.22**	**50.50**	**2.84**	**5.95**	**2.76**	**25.59**	**31.24**	**30.18**

AC I (Age class I—$\leq$ 5 years); AC II (5–10 years); AC III (10–15 years); D1—soil depth 0–20 cm; D2—20–40 cm; D3—40–60 cm.

Regular litter input along with moderate temperature and humidity in the *Gmelina*-based land use caused higher availability of organic carbon (OC) and nutrients on the surface than the subsurface layers [51]. The availability of soil primary nutrients in plantations was in the order N > K > P [36,52]. The estimated available amount of these primary nutrients indicates that soil in the *Gmelina* farm was low-medium in available nitrogen, low-high in available phosphorus, and low in available potassium [53]. Available soil nitrogen and potassium were synergistic to each other [54]. Forest and cultivated unmanaged land were estimated with highest available amount of nitrogen and organic carbon, while these are medium in well-managed cultivated soil and lowest in barren land [55]. Similar to the soil properties in the plantations, the amount of available SOC and soil primary nutrients also differed significantly but without any visible trends with increasing age of the plantations indicating local differences (Supplementary Tables S8–S11). These differences were due to variations at the microlandscape level in site quality factors associated with socio-ecological conditions such as vegetation parameters and management of surrounding crop fields [50].

The estimated amount of available SOC and primary nutrients was staggered at different soil depths with no discreet trend, indicating highly inconsistent nature and unstable characteristics of soil in the *Gmelina* farm [42]. Similar heterogeneity of soil properties with no discreet trend observed in the present study area was also reported from urban plantations [56]. Adequate soil management is crucial for nutrient availability and OC [57]. Forests were converted to agricultural lands in the Terai region of West Bengal and generally were not adequately managed, which resulted in the inconsistent and unstable nature of soil indicated by the unpredictable behavior of soil properties including less nutrient availability and OC build up than the natural forests [58]. The plantations were established in unused or fallow crop land and kept undisturbed except FYM application during planting and at the most once after one year of planting. The growing plantation used nutrients from the soil with no or very little replenishment in the soil from litter input initially. Moreover, there was also lesser understory vegetation during the initial years of plantation establishment adding less organic matter to the soil. With the continuous growth of trees and increase in understory vegetation due to no management of the plantations, there was nutrient build by organic matter (litter) input and thus the amount of soil available nutrients did not exhibit any discreet trend with increasing age of the plantations.

Factors such as topography, climate (temperature, precipitation, RH), weathering process, vegetation cover, and microbial activities influence the build-up of OC and nutrients in the soil [48]. Differences in the replenishment of nutrients back to the soil due to varied litter input, soil water content, aeration, temperature, microorganisms, and efficiency of the root system to absorb nutrients caused variation of feedback mechanism of various ecosystem processes in the plantations [59]. *Gmelina* farm forestry plantations of different age groups were thus vegetation with heterogeneous structures and compositions that caused significant variation among their SOC build up and nutrient availability [60]. The structures and compositions of vegetation and soil properties are positively correlated with available SOC and nutrients [61]. There are abundant reports on negative influence of forest conversion to crop land or plantation [62]. Tree-based land uses and management practices, however, positively change the soil properties including SOC build up [36].

Contrary to the reports of higher availability of soil primary nutrients due to higher soil organic matter in the tree-based land uses [33], the present study found no such trends with the availability of soil primary nutrients with available C build up in the plantation soil. Application of FYM at the early stage of plantation establishment might be the reason for no such trends in the plantations. Further, human activities in and around the plantations were also responsible for the unpredictable behavior of soil properties in the plantations [63]. Trends or no trends, soils under *Gmelina* farm in the Terai region of West Bengal without any management also accumulated a considerable amount of carbon and primary nutrients sometimes comparable to forest and well-managed agricultural land uses [64]. However, the process of carbon accumulation in soils of *Gmelina* farm forestry plantations was still left largely unexplained akin to other studies [64].

3.5. Biomass Production and Biomass Carbon Stock

The AGB, BGB, and total biomass with their corresponding C quantified for the *Gmelina* farm are given in Table 5. The overall contribution of AGB in the plantations was 87.37% to the total biomass. Overall in the plantations, trees contributed 96.72%, litter contributed 3.17% and understory shrubs and herbs contributed only 0.11% of the total biomass in the plantations, while overall in the plantations only *Gmelina* trees contributed 34.35% and associated trees contributed 62.37% of the total biomass. The biomass of the plantation increased gradually with its increasing age, exhibiting a strong positive correlation (r = 0.795; Table 3)—i.e., the biomass of the plantations increased with increasing age. The quantum of biomass increases were higher from AC II to AC III (21.19% for above ground, 21.26% for below ground, and 21.20% for total biomass) than from AC I to AC II (4.07% for above ground, 2.66% for below ground and 3.89% for total biomass). ABG, BGB, and TB of *Gmelina* were increased by 9.37, 9.28 and 9.36% from AC I to AC II, respectively; while the increases were 19.39, 19.5 and 19.4% from AC II to AC III, respectively. In age class I, mean contributions of total AGB, litter biomass and total shrubs + herbs biomass to mean total biomass of the plantations were 87.27, 2.43, and 0.1%, respectively, while contributions of *Gmelina* and associated trees AGB, BGB, and TB to mean total biomass of the plantations were 28.98, 4.35, 33.33, 55.77, 8.34, and 64.1%, respectively.

Table 5. Biomass and carbon stock (Mg ha^{-1}) in *Gmelina* farm forestry plantations.

Component	AGB	BGB	TB	AGC	BGC	TC
Age class I (≤ 5 years)						
Gmelina arborea	31.6	4.74	36.34	15.8	2.37	18.17
Bombax ceiba	12.24	1.84	14.08	6.12	0.92	7.04
Melia azaderach	2.20	0.33	2.53	1.1	0.16	1.26
Ailanthus grandis	5.36	0.80	6.16	2.68	0.4	3.08
Chukrasia velutina	2.15	0.32	2.47	1.07	0.16	1.23
Tectona grandis	10.26	1.54	11.8	5.13	0.77	5.59
Swietenia macrophylla	13.45	2.02	15.47	6.72	1.01	7.73
Dalbergia sissoo	2.72	0.41	3.13	1.36	0.20	1.56
Albizia lebbeck	12.42	1.86	14.28	6.21	0.93	7.14
Shrub	0.045	0.007	0.052	0.0225	0.0035	0.026
Herb	0.053	0.008	0.061	0.0265	0.004	0.031
Litter	2.65	-	2.65	1.32	-	1.32
Total	**95.15**	**13.88**	**109.03**	**47.57**	**6.94**	**54.51**
Age class II (5–10 years)						
Gmelina arborea	34.56	5.18	39.74	17.28	2.59	19.87
Melia azaderach	2.68	0.4	3.08	1.34	0.2	1.36
Chukrasia velutina	9.1	1.36	10.46	4.55	0.68	5.23
Bombax ceiba	17.22	2.58	19.8	8.61	1.29	9.9
Tectona grandis	20.64	3.1	23.74	10.32	1.55	11.87
Ailanthus grandis	7.16	1.07	8.23	3.58	0.53	4.11
Syzygium cumini	3.59	0.54	4.13	1.79	0.27	2.06
Shrub	0.054	0.008	0.062	0.027	0.004	0.031
Herb	0.062	0.009	0.071	0.031	0.004	0.035
Litter	3.95	-	3.95	1.97	-	1.97
Total	**99.02**	**14.25**	**113.27**	**49.51**	**7.12**	**56.63**
Age class III (10–15 years)						
Gmelina arborea	41.26	6.19	47.45	20.63	3.09	23.72
Melia azaderach	7.21	1.08	8.29	3.6	0.54	4.14
Chukrasia velutina	6.32	0.95	7.27	3.16	0.47	3.63
Bombax ceiba	16.68	2.50	19.18	8.34	1.25	9.59
Tectona grandis	20.36	3.05	23.41	10.18	1.52	11.7
Ailanthus grandis	12.4	1.86	14.26	6.2	0.93	7.13
Syzygium cumini	10.84	1.63	12.47	5.42	0.81	6.23
Shrub	0.057	0.008	0.065	0.028	0.004	0.032
Herb	0.073	0.011	0.084	0.036	0.0055	0.042
Litter	4.80	—	4.80	2.40	—	2.40
Total	**120.0**	**17.28**	**137.28**	**60.0**	**8.64**	**68.64**
Mean of all age classes	**104.72**	**15.14**	**119.86**	**52.36**	**7.55**	**59.91**

AGB: above-ground biomass; BGB: below-ground biomass; TB: total biomass; AGC: above-ground carbon; BGC: below-ground carbon; TC: total carbon.

Prominent tree species associated with AC I were Bombax ceiba, Melia azaderach, Ailanthus grandis, Chukrasia velutina, Tectona grandis, Swietenia macrophylla, Dalbergia sissoo and Albizia lebbeck, contributing 12.88, 2.32, 5.65, 2.26, 10.82, 14.19, 2.87, and 13.10%, respectively, to the total plantation biomass. Similarly, in AC II the contributions of total plantation AGB, litter biomass, total shrub + herb biomass, and above-ground, below-ground and total biomass of Gmelina and associated trees to total plantation biomass were 87.42, 3.49, 0.12, 30.51, 4.57, 35.08 and 61.30%, respectively, while in AC III the contributions were 87.41, 3.5, 0.11, 30.06, 4.51, 34.56 and 61.83%, respectively. Melia azaderach, Chukrasia velutina, Bombax ceiba, Tectona grandis, Ailanthus grandis, and Syzygium cumini were associated with both AC II and AC III age group plantations and their contributions of total biomass to the total plantation biomass were 2.72 and 6.04%, 9.23 and 5.29%, 17.48 and 13.97%, 20.96 and 17.06%, 7.26 and 10.39% and 3.65 and 9.08%, respectively. The amount of biomass estimated in the Gmelina farm forestry plantations was less than that reported from plantation or stands in forest landscape from the same study area—i.e., Terai zone of West Bengal [65]. Negligible contribution of understory vegetation and significant contribution by above-ground parts to the total biomass of the tree-based land uses was also reported by many previous works [66].

With increasing age, biomass increased with no change in the contribution of both AGB and BGB towards total biomass from AC I to AC II and AC II to AC III. The contributory trend of the different components of the *Gmelina* plantation towards total mean biomass with increasing age also remained unchanged with increasing age of the plantation. Litter production though increased with increasing age of the plantation but also exhibited the same contributory behavior towards total mean biomass. *Bombax ceiba*, *Melia azaderach*, *Ailanthus grandis*, *Chukrasia velutina,* and *Tectona grandis* were found in all the age classes of *Gmelina* farm forestry plantations. The total biomasses of these associated tree species in ACs I, II, and III were 37.04, 65.31 and 72.41 Mg ha^{-1} which were 33.97, 57.66, and 52.74%, respectively, of the total plantation biomass. From AC I to AC II, the contribution of these five associated species increased by 23.69% but from AC II to AC III their contribution decreased by 4.92%. The total biomass contribution of *Gmelina* was 33.33%, 35.08%, and 34.56% towards total plantation biomass in AC I, AC II, and AC III, respectively. The trend in contribution of total biomass towards total plantation mean biomass to the next higher age class by the five common associated species and *Gmelina* was similar but the quantum of change was more for the five associated species considered together than the *Gmelina*.

The change and dynamics of contribution by the components of *Gmelina* farm towards total biomass can be explained by the increase in and intensity of both inter- and intraspecific competition. Carbon is considered half of biomass, so any factor (biomass and carbon) change that influences both [20] thus exhibits the same trends as exhibited by the biomass with increasing age of the plantation. Biomass and biomass carbon varies with land use, climatic conditions, edaphic conditions, topography, site quality, age, species diversity, stem density, stem size distribution, density, structure, litter production, management practices, and disturbance history along with variations in canopy height and wood density [67]. Similar quantification of biomass accumulation and carbon storage in eucalyptus plantations was also reported by Kumar et al. [68]. Quantification of biomass in tree plantations at agricultural landscape will aid in formulating sustainable management strategies for increasing carbon pool build up outside forest land use [20].

3.6. Ecosystem Carbon Stock

The overall ecosystem C values estimated in the three age classes were 110.24, 104.81 and 110.77 Mgha^{-1} (Tables 4 and 5). The present study was unable to make a direct and accurate estimation of C uptake by the vegetation because of high variability in tree distribution and species causing uncertainties, as was also earlier reported [69,70].

Promoting plantations of suitable site-specific tree species in less or unproductive and degraded agricultural lands is a recognized management action for offsetting terrestrial C emission because of longer duration C storage both in biomass and soil [71]. Forests are now net emitters due to degradation and deforestation [72]. Changing the forests to net sink again from net emitter will need a supplement of additional C emission offset by the best available land management options through promoting afforestation/reforestation of available degraded and deforested lands [33]. Managing soil and biomass C in an agricultural landscape by promoting *Gmelina arborea* or any other tree species plantation will both be an avoided emission and net addition of C to terrestrial pools, thereby fulfilling the global four per mile initiative [71]. The studied *Gmelina* farm forestry plantations with only three age class series had considerable vegetation heterogeneity due to no disturbance or management which if allowed growing full normal rotation period with selective logging, development of seminatural secondary forest is expected [73].

4. Conclusions

Farm forestry is now globally recognized as a low-cost viable option to supplement forests in an effort to offset carbon (C) emissions. Younger *Gmelina* farm plantations (up to 15 years of age) left aside after planting without silvicultural management in the Terai region of West Bengal has the great potential of carbon sequestration due to their biomass and soil. The ecosystem C in the three age classes (ACs I, II, and III) of plantations was in the range of 104.81–110.77 Mg ha^{-1}, of which carbon storage by tree and soil carbon as SOC (up to 60 cm depth) were in the range of 54.51–59.91 and 48.18–55.73 Mg ha^{-1}, respectively. This C storage is mainly from young plantations and can play an important role if allowed to complete a normal rotation cycle of 60–80 years. Further, a rotation cycle without any disturbance with selective logging can develop considerable vegetation heterogeneity which might lead to the conversion of homogenous plantations into seminatural secondary forests. These microlandscapes within agricultural or human-dominated landscapes will act as an oasis for biodiversity conservation. Further, carbon sequestration potential of *Gmelina arborea* is reported to be higher compared to other species and very much supportive for atmospheric carbon reduction in future under higher temperatures by implementing a strategic plant diversity conservation plan.

5. Recommendations and Future Directions

This study recommends popular plantation programs through mission mode with these high value timber species as C farming initiatives either in the unproductive and degraded nonforested or agricultural landscapes. Popularizing such plantation programs needs policy decisions and action with suitable site-specific tree species in participatory mode with intensive growth. Plantations were generally thought to limit biodiversity and are developed by the owner for economic benefits [74]. These allegations can be cleared up by adopting different site-specific management strategies by removing disturbance factors to allow heterogeneity of the landscape so that seminatural forest vegetation within the agricultural or any other nonforested landscape is developed without compromising the timber demands while bringing social and ecological benefits [75]. This requires further studies to understand the plantations at various successional stages throughout the age classes of natural rotation of species. The effect of plant community composition on ecosystem functioning and services is yet to be understood [25]. Establishing plantations with higher diversity of indigenous tree species is required for studying this relationship. In farm tree plantations, plant life-history strategies require clear understanding to analyze patterns of biomass allocation and partitioning in various tree species for sustainable tree-based land management strategies and identifying the most productive tree species for C sequestration [76]. Driving mechanisms of terrestrial C sinks and/or sources with their regional patterns and magnitudes are unclear [77]. Therefore, there is a need to work for the success of these plantations for C reduction. Even now, uncertainties prevail over quantifying C fluxes in and out of a system due to insufficient pieces of information about land use and land cover changes [78]. Thus, information on C exchange between these plantations and atmosphere needs urgent attention for efficient C budgeting for viable policy support and strategic decisions.

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