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Soil Properties, Litter Dynamics and Biomass Carbon Storage in Three-Bamboo Species of Sub-Himalayan Region of Eastern India

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Abstract Information on biomass carbon storage in bamboo plantations/groves at local or regional landscapes is crucial to understand its potential in carbon stock management and climate change mitigation. The present work aims to study soil properties, litter dynamics and biomass carbon storage for the three common bamboo species from the Terai region of Indian Eastern Himalayas. *Bambusa nutans*, *Dendrocalamus giganteus* and *Melocanna baccifera* groves were selected for the present study. The soil pH, moisture and electrical conductivity under different bamboo groves of three species varied significantly, but moisture and electrical conductivity responded inconsistently with increasing soil depth. Similarly, the amount of soil available primary nutrients also varied significantly, where soils of *M. baccifera* grove were quantified with highest amount of these nutrients at all depths. *M. baccifera* grove produced the highest litter, although the difference with the other two groves was non-significant. The amount of oxidizable soil organic carbon quantified varied significantly among the bamboo groves, with the highest SOC content under the *M. baccifera* grove. The decomposition rate gradually increased with time, and within 9 months, the entire litter got decomposed. The annual return of nutrients was in the order N > K > P. The total biomass of *D. giganteus*, *B. nutans* and *M. baccifera* was estimated at 270.97, 127.21 and 16.31 Mg ha^{-1}, respectively. Based on the higher R^2 and adj R^2, and lower AIC and HQC, Model 1 was more appropriate for *B. nutans* and *D. giganteus*, whereas Model 2 was suitable for *M. baccifera*. The ecosystem carbon stock of *D. giganteus* was significantly (163.28 Mg ha^{-1}) higher than the other two species because of its significantly higher biomass carbon accumulation. This amount of biomass carbon storage and ecosystem carbon stock is comparable with agroforestry and forest ecosystems in the study region or elsewhere. The present study suggests these bamboos can be a feasible option for carbon farming and carbon trading, climate change adaptation and mitigation, apart from its contribution in social and economic contributions to the region's rural life. Therefore, value addition and nationalizing of bamboo are recommended to improve rural folks' livelihood. Encouraging value-added bamboo products can be negative feedback to climate change because of their durability and thus permanency of carbon stored in it.

Keywords Bamboo · Biomass · Soil carbon · Litter · Climate change · Himalayas

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1 Introduction

Bamboos, essential constituents of rural landscapes of India and other countries (Chakravarty & Shukla, 2012; Nath et al., 2009; Ram et al., 2010; Zhang et al., 2014), are important biomass resources of developing tropical countries (Darabant et al., 2014; Singnar et al., 2017; Yen, 2016; Yuen et al., 2017). Unlike other timber species or other cash crops, bamboos grow faster with higher biomass productivity and faster maturation, requiring very little or no inputs for its management (Nath et al., 2015; Tariyal et al., 2013). In tropical areas, bamboos are essential for their practical, economic and environmental services at the village and forest ecosystem level (Nath et al., 2009) and provide raw materials for the industries. With 11.4 million hectares of bamboo growing area under agrisilviculture systems and forests, India is the major bamboo-producing country in Asia (Nath et al., 2009; Seethalakshmi et al., 2009). In West Bengal, bamboos occur mainly as understorey vegetation in forests and grown in homegardens, mainly in the subhumid Himalayan foothill region or the Terai region (Chakravarty & Shukla, 2012).

Soil particularly of perennial vegetation like bamboo grove have higher organic matter and thus considered an essential terrestrial carbon sink (Nath et al., 2015, 2018; Shukla et al., 2017a). This sink is primarily regulated through litter influx that supplies organic matter to the soil, responsible for the uninterrupted cycling of materials and energy in the system (Chakravarty et al., 2020; Nair et al., 1999). Litterfall is thus pivotal to regulate this cycle, as it is the fundamental source of energy and nutrients in a system, including bamboo groves (Chakravarty et al., 2020). Furthermore, the decomposition process releases nutrients essential for plant growth and development (Chakravarty et al., 2020; Polyakova & Billor, 2007; Shukla et al., 2017a). Nutrient utilization by plants and its return to the soil through the litter, in turn, influences soil physico-chemical properties of the systems (Chakravarty et al., 2020; Rawat et al., 2010), which need to be analyzed and quantified in bamboo groves. Additionally, bamboos, especially for their fast growth and high regeneration rate after harvesting, can rehabilitate degraded land more quickly than trees (Mishra et al., 2014). Therefore, information on the litter dynamics potential of bamboo will advance our understanding of its role in soil health management.

Bamboo biomass is commonly estimated through species-specific and multi-species allometric equations to compute its biomass and carbon stocks (Xayalath et al., 2019). Different independent variables for developing biomass models are still a subject of empirical debate (Nath et al., 2019). Diameter at breast height (*D*) and total tree height (*H*) have been used widely for modelling scaling relationships between tree biomass components, H and D, assuming different physical and biological first principles (Sileshi, 2014; Singnar et al., 2017). Bamboos provide numerous ecosystem services but remain unexplored for their potential for carbon farming or trading (Lobovikov et al., 2012; Nath et al., 2015). Bamboo can be a viable option for climate change mitigation and adaptation strategies globally (Darcha & Birhane, 2015; Nath & Das, 2011a, 2012; Wang et al., 2013). Specifically, for the Terai region, the information on biomass carbon storage potential for bamboo, species are lacking and therefore an in-depth study will advance our understanding on the carbon farming potential of those species.

With all these in view, the present study was framed with the following objectives: (i) to estimate soil physico-chemical parameters under the bamboo canopy, (ii) to quantify litter and its nutrient dynamics, and (iii) to estimate standing biomass and carbon storage of bamboos in the Terai region of India.

2 Materials and Methods

2.1 Site Description

The study site is located in Pundibari falls under the Terai zone in the eastern humid sub-Himalayan region of India. The study site is located at 26º19′ 86″ N Latitude and 89º23′ 53″E Longitude at an elevation of 43 and characterized by a sub-tropical climate. The total annual rainfall received was about 2600 mm, of which 80% was recorded during June–August, and relative humidity ranged from about 46 to 94%. The rainfall in the Terai zone of West Bengal is due to south-west monsoon. The summer and winter temperatures are mild, with the highest of 36ºC during April–May and the lowest of 6ºC during February. The average meteorological data of the study site from September 2017 to April 2019 is given in Fig. 1. The soil of the Terai zone in West Bengal is acidic, high in organic carbon and available nitrogen, medium in phosphorus and potash (Shukla et al., 2017a, 2017b).

Bamboo groves of *Bambusa nutans*, *Dendrocalamus giganteus* and *Melocanna baccifera* were selected for the present study. For each species, four 20 m × 20 m size quadrat was laid in a bamboo grove. Therefore, a total of 36 such quadrats (12 each for a species) were laid for the present study.

2.2 Soil Sampling and Analysis

Composite soil samples were collected under the bamboo canopy (1 m away from the main bamboo clump) once separately from 0-–20-, 20-–40-, and 40-–60-cm depth with Dutch augur from the marked quadrats. Soil samples were air-dried in the shade, ground with a wooden pestle, passed through a 2-mm sieve and stored in cloth bags for further laboratory analysis. The following soil parameters were analyzed following the method given below.

Soil parameters	Methods
Moisture	Volumetric method
pH (1:2 soil: water suspension)	Beckman's pH meter (Jackson, 1967)
Electrical conductivity (m mhos/ cm) at 25 °C (1:2 soil water suspension)	Solubridge conductivity meter
Soil organic carbon (%)	Walkley and Black's rapid titration method (Jackson, 1967)
Available N kg ha^{-1}	Modified Kjeldahl method (Jackson, 1967)
Available P kg ha^{-1}	Bray's method (Jackson, 1967)
Available K kg ha^{-1}	Jackson, 1967

The SOC stock was expressed as Mega gram per ha^{-1} (Mg ha^{-1}) for a specific depth and was computed by multiplying the soil organic carbon with bulk density and depth.

2.3 Litter Sampling and Analysis

Standing litter on the floor was collected once during May 2018. Three 1 m × 1 m sub-quadrates were placed diagonally (two at opposite corners and one in the centre) within all the quadrates, and the litter mass therein were collected. Litter collected was brought to the laboratory and oven-dried at 80ºC until the dried samples' weight became constant. The dried litter was then weighed to quantify the litter production in mega grams per hectare for each species separately (Rai et al., 2021). Oven-dried litters (25 g) were put in the 2-mm mesh nylon bags of size 15 cm × 15 cm. 36 bags (12 bags for each species) were placed on the soil floor (in the vicinity of a particular clump of the species) for decomposition. Nine bags (three bags for each species) were retrieved at 3-month interval. Decomposed materials were brought to the laboratory in polythene bags, air-dried in the shade, ground with

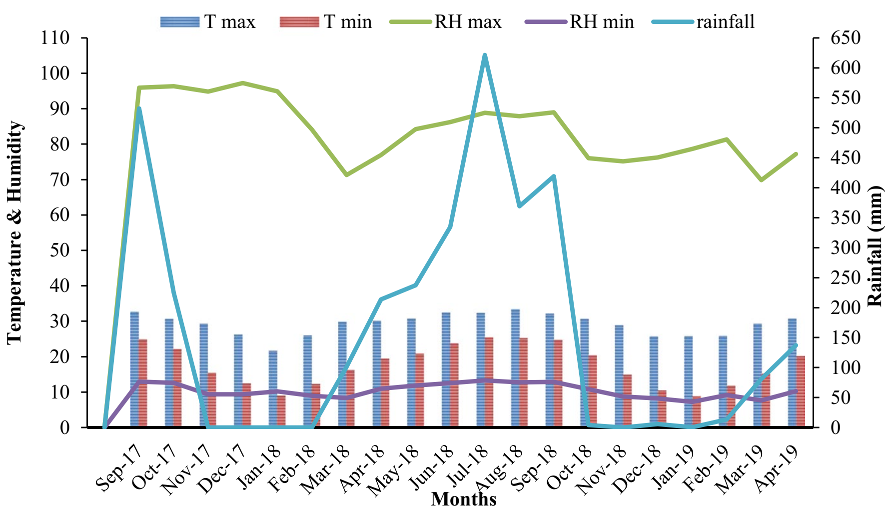


Fig. 1 Metrological Data During the Study Period

an electric grinder and then analyzed for chemical parameters (Krishna & Mohan, 2017; Pande, 2001). Litter samples were analyzed for organic carbon and available nutrients following the method given above for soil analysis.

2.4 Biomass Sampling and Analysis

Destructive sampling was adopted for biomass measurement of the bamboos 300 culms (100 for each species) was selected randomly from 36 quadrates for harvest to measure height and diameter. Clumps were also categorized into four age classes i.e. 1–4 years of age (Singnar et al., 2017). From each age class, at least 25 culms were harvested. The culm, sheath, leaves and twigs were separated and weighed. The stump of the harvested culms was excavated from the soil and weighed. The length of the culm was measured to record its height, and the diameter of the culm was measured with a vernier calliper. The above and below-ground biomass of the bamboo species were estimated (Singnar et al., 2021) and expressed in mega gram per hectare.

2.5 Estimation of Carbon

The total biomass estimated in a quadrate was converted into carbon by multiplying with a factor of 0.50 (IPCC, 2003).

2.6 Biomass Model Development

The appropriateness of a simple power-law relationship between above ground biomass (AGB), DBH and culm height (*H*) was explored (Singnar et al., 2017). This is because power-law scaling is supported by emergent macro-ecology theories and thus recommended in biomass estimation to reduce the ambiguity about allometric relationships. Finally, the power-law model's performance with two other models involving D alone and H alone was compared. When fitting the models, log-transformed biomass data were linearly regressed against the log-transformed values of *D* and *H*.

2.7 Statistical Analysis

Data were analyzed by one-way analysis of variance using Gen Stat version 11.1.0.1504 (VSN International Ltd. Oxford, UK). The bamboo data were also subjected to one-way ANOVA using Statistical Software R 3.5.3 (https://cran.r-project.org/).

3 Results and Discussion

3.1 Soil Parameters

The pH, EC and soil moisture of different bamboo species at three soil depths are given in Table 1. The soil pH under three species varied significantly. The bamboo groves' pH was slightly acidic, but as soil depth increased, acidity of the soil decreased. The pH range irrespective of species was 6.10-–6.13-, 6.14-–6.93-, and 6.20-–6.93- at 0-–20-, 20-–40-, and 40-–60-cm soil depth. The surface layer was more acidic as compared to the sub-surface layer in all stands.

Accumulation of more humus due to litter's presence in the top layer makes the soil floor more acidic than the subsoil layers. Soils with vegetation cover generally have a pH range of 5.0–6.8 (Gairola et al., 2012; Sheikh & Kumar, 2010; Shukla, 2010).

Table 1 Soil physical parameters of bamboo groves

Species	pH			EC (decisiemens m^{-1})			Moisture (%)		
	D_1	D_2	D_3	D_1	D_2	D_3	D_1	D_2	D_3
Dg	6.13	6.14	6.20	0.08	0.06	0.08	35.07	36.66	35.56
Bn	6.10	6.93	6.93	0.06	0.09	0.08	28.33	27.86	27.37
M b	6.11	6.40	6.40	0.07	0.08	0.07	37.63	33.75	35.52
SE_m	**0.003**	**0.003**	**0.003**	**0.001**	**0.001**	**0.001**	**0.23**	**0.40**	**0.34**
$LSD_{p=0.05}$	**0.009**	**0.01**	**0.008**	**0.003**	**0.003**	**0.002**	**0.68**	**1.18**	**1.00**

D g *Dendrocalamus giganteus,* B n *Bambusa nutans,* M b *Melocanna baccifera,* D_1 0–20 cm, D_2 20–40 cm, D_3 40–60 cm.

The soils under bamboo groves were more or less undisturbed, leading to accumulation of organic matter through litter fall and following its rapid decomposition the leaching of bases increased the soil EC while, lowering the pH (Khera et al., 2001; Paudel & Sah, 2003; Paul, 2004).

Similarly, the soil moisture and EC of all the bamboo groves varied significantly, yet, the increment with increasing soil depth was not consistent. The soil of the moist sub-Himalayan region belongs to orders Inceptisol and Entisol, which was developed by depositions brought down by the rivers (Mondal et al., 2002). These soils are considered immature, where the soil horizonation processes is still formative, resulting in inconsistent soil properties across its depth (Weil & Brady, 2017). Similar soil moisture and EC values of soil with vegetation cover were also reported by other studies (Sheikh & Kumar, 2010; Shukla, 2010; Shukla et al., 2017b). The soil moisture under the *D. giganteus* and *M. baccifera* grove was estimated at 35.07 and 37.63% at 0-–20-cm soil depth, 36.36 and 33.75% at 20–40 cm and 35.56 and 33.52% at 40-–60-cm soil depth, respectively. In *Bambusa nutans* at these soil depths, the soil moisture was 28.33, 27.86 and 27.37%, respectively. The EC estimated for *D. giganteus*, *M. baccifera* and *B. nutans* groves for 0-–20-, 20-–40- and 40-–60-cm soil depth was 0.08, 0.06 and 0.08, 0.07, 0.08 and 0.07 and 0.07, 0.08 and 0.07 decisiemens m^{-1}, respectively. Soil moisture regime under vegetation is a function of many factors like soil texture and structure, rainfall, amount of radiation received on the floor, aridity, humidity and temperature (Pande, 2001). The study area has humid climatic conditions (Fig. 1). A continuous canopy cover of the bamboo groves had intercepted most solar radiation, causing less evaporation, thereby conserving high soil moisture in the bamboo groves. Moreover, the humus layer presents reduced evaporation, increased water infiltration, absorbed and retained substantial water quantities (Poorter et al., 2017). Soil moisture in *B. nutans* grove was significantly lesser than the *D. giganteus* and *M. baccifera* groves because of the more sandy soil than the other bamboo groves.

The available nitrogen, phosphorus and potassium in the soil of *D. giganteus*, *M. baccifera* and *B. nutans* groves at 0-–20-, 20-–40- and 40-–60-cm depth is presented in Table 2 and the availability of these nutrients was significantly different among these species.

The soils of *M. baccifera* grove were estimated with the highest amount of nitrogen, phosphorus and potassium at all depths with 253.0, 67.7 and 122.4 kg ha^{-1} at 0-–0 cm; 193.4, 51.5 and 107.6 kg ha^{-1} at 20–40 cm and 190.1, 41.5 and 99.0 kg ha^{-1}at 40-–60-cm soil depth, respectively. The amount of available nitrogen and potassium at soil depths was least in *B. nutans*, while phosphorus was least in *D. giganteus*. This is because *M. baccifera* grove produced the highest amount of litter (Fig. 2), and subsequently released more nutrients in the soil.

Moreover, litter provides carbon and energy to microorganisms, which might have increased the microbial biomass pool. The increase in microbial biomass pool increased soil respiration rates, enhancing the available soil nitrogen in the bamboo groves of *M. baccifera* (Hariprasath et al., 2014; Surekha et al., 2004). In addition, the production of more organic acids in the soils of *M. baccifera* groves resulted in a higher soil available amount of phosphorus than the other two bamboo species (Lal et al., 2000). Similar amounts of available nitrogen, phosphorus and

Table 2 Available soil primary nutrients (kg ha^{-1}) in bamboo groves

Species	Nitrogen			Phosphorus			Potassium		
	D_1	D_2	D_3	D_1	D_2	D_3	D_1	D_2	D_3
Dg	216.4	188.2	185.0	44.8	41.0	41.0	122.2	106.2	96.7
Bn	197.6	187.1	156.8	55.9	47.7	28.1	81.9	80.1	75.4
M b	253.0	193.4	190.1	67.7	51.5	41.5	122.4	107.6	99.0
SE_m	**3.1**	**1.7**	**2.8**	**2.0**	**1.8**	**0.2**	**1.1**	**1.5**	**0.5**
$LSD_{=0.05}$	**9.2**	**4.9**	**8.2**	**5.8**	**5.2**	**0.6**	**3.1**	**4.3**	**1.5**

D g *Dendrocalamus giganteus,* B n *Bambusa nutans,* M b *Melocanna baccifera,* D_1 0–20 cm, D_2 20–40 cm, D_3 40–60 cm.

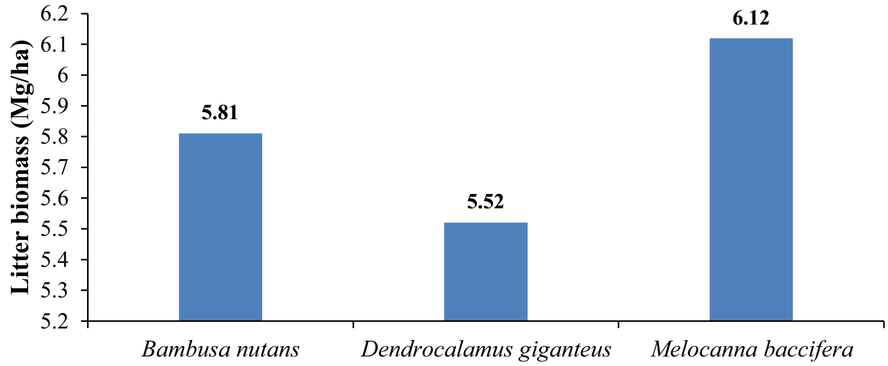


Fig. 2 Standing litter mass (Mg ha^{-1}) in bamboo groves

Table 3 SOC stock (Mg ha^{-1}) in bamboo groves at different depths

Species	0–20 cm	20–40 cm	40–60 cm	Total
Dendrocalamus giganteus	9.63_b	7.83_b	7.53_b	$\mathbf{24.99_b}$
Bambusa nutans	13.46_a	7.29_b	5.36_c	$\mathbf{26.11_b}$
Melocanna baccifera	13.76_a	9.69_a	9.79_a	$\mathbf{33.24_a}$
SE_m	**0.22**	**0.23**	**0.16**	**0.36**
$CD_{p = 0.05}$	**0.70**	**0.75**	**0.50**	**1.14**

Figures followed by the same letters in a column are not significantly different from each other according to Tukey's HSD test.

potassium were also reported from *Bambusa vulgaris*, *B. balcooa*, *B. nutans* and *D. strictus* plantations (Hariprasath et al., 2014; Tariyal et al., 2013).

Total nitrogen, available phosphorus and potassium are positively correlated with organic carbon because all these attributes were intimately linked with soil humus (Gairola et al., 2012; Gupta & Sharma, 2008). Soil organic matter (SOM) is replenished by litter fall, which influences soil texture, water-holding capacity, pH and nutrients availability. However, these attributes may vary spatially and temporally due to variation in topography, climate, weathering process, vegetation cover and microbial activities (Paudel & Sah, 2003). However, all three-bamboo species' soil was low in available nitrogen, high in available phosphorus and low to medium in available potassium (Tandon, 2005). The nutrient availability in the soil of *D. giganteus*, *M. baccifera* and *B. nutans* groves were in the order N > K > P, which decreased gradually with the increase in soil depth. Similar order and availability of these nutrients from different forest plantations were also reported (Pande, 2001), including West Bengal's Terai zone (Rai et al., 2021; Shukla et al., 2017b).

The amount of soil organic carbon (SOC-oxidizable) in the bamboo groves at different depths is given in Table 3, and it varied significantly among the three-bamboo species.

Consequent to the *M. baccifera* grove's highest litter production, the amount of SOC estimated in the grove was also the highest. A higher SOC content is due to litter addition which regulates organic matter decomposition and formation of stable and labile soil organic matter pool (Naitham & Bhattacharyya, 2004; Singh et al., 2004). Generally, the increase in soil organic matter is due to leaf litter's annual addition (Joao Carlos et al., 2001; Jha et al., 2003). Soil organic matter is the primary building block of the SOC, which regulates the soil's physical, chemical and biological properties (Jha et al., 2003). Moreover, as the soil depth increased, the amount of SOC content decreased. This is because the soil surface layer contains a higher amount of organic matter that decreases with soil depth. The organic carbon content decreases with the soil depth due to humus formation and decomposition of organic matter in the upper layers.

The total amount of SOC for 0-–60-cm soil depth was in the range of 24.99–33.24 Mg ha^{-1}, which is far less (57–200 Mg ha^{-1}) than the earlier studies involving different species of bamboo (Hariprasath et al., 2014; Thokchom & Yadava, 2017; Yuen et al., 2017). Soil carbon was reported highly variable both spatially and temporally from micro to global landscapes in terms of latitude, longitude and net primary productions with the maximum at higher latitudes, decreases in mid-latitudes and increases in humid tropics (Kerry et al., 2012; Minasny et al., 2017; Scharlemann et al., 2014). The earlier studies reported SOC (1.5–2.5%) of pure bamboo plantations in forest landscapes. The present study's SOC estimates were only 0.22–0.63% from small bamboo groves in an agricultural landscape. This indicates that the bamboo groves in the agricultural landscape of West Bengal's Terai zone were low to medium in SOC (Tandon, 2005). Higher SOC content (1.03–1.81%) was also reported from the Terai zone forest in West Bengal (Koul, 2004; Shukla, 2010). Temperate regions can accumulate a higher amount of organic matter in the soil due to slower decomposition rates. Low temperature restricts decomposition rates (Jha et al., 2003; Minasny et al., 2017). The reverse condition prevailing in the Terai zone of West Bengal having a humid tropical climate explains the lesser total SOC in its soil (Marín-Spiotta & Sharma, 2013).

4 Litter Production and Decomposition

Initial litter amount and amount of litter material decomposed at 3-month interval of the bamboo groves are given in Table 4. The amount of litter mass-produced by *D. giganteus*, *B. nutans* and *M. baccifera* groves during the time of observation was 5.52, 5.81 and 6.12 Mg ha^{-1}, respectively, and was statistically non-significant. A similar amount of litter was estimated for *B. bamboo* stands at deciduous forests of Western Ghats (Nisharaj et al., 2003). A much higher litter production (15.4–20.3 Mg ha^{-1}) was reported from *Bambusa bamboo* plantations in Tamil Nadu (Shanmughavel et al., 2000).

The return to soil through decomposition from initial litter mass was slow initially because of lignin (Sangha et al., 2006). However, after the decomposition of lignin from the litter mass, the decomposition rate gradually increased with time, and within 9 months, the entire litter mass got decomposed. In contrast, it took twice the more time to completely decompose litters under the *Dendrocalamus strictus* plantation in the dry tropical region of northern India (Singh & Singh, 1999). This may be due to favourable temperature, optimum rainfall and soil moisture (Table 1) regime prevailed in the study area, which is humid tropical. Plant litters' decomposition rate and nutrient release are mainly controlled by environmental conditions, composition, soil organisms' activities and the substrate's chemical quality (Bradford et al., 2016; García et al., 2016; Krishna & Mohan, 2017). It is widely believed that plant litter decomposes rapidly and entirely in humid tropics because humidity and temperature favour microbial activity (Tariyal et al., 2013).

The amount of nitrogen, phosphorus and potassium in the fresh and decomposing litter at 3 months is given in Table 5. The three-bamboo species are statistically at par in terms of nutrient return from their litter through decomposition. A similar amount of litter was estimated for *B. bamboo* stands at deciduous forests of Western Ghats (Nisharaj et

Table 4 Initial and periodic decomposed litter (Mg ha^{-1}) of bamboo groves

Species	Initial	After 3 months	After 6 months
Dendrocalamus giganteus	5.52	0.27_b	2.63
Bambusa nutans	5.81	0.44_b	2.15
Melocanna baccifera	6.12	0.90_a	2.54
SE_m	**0.58**	**0.10**	**0.36**
$CD_{p=0.05}$	NS	**0.34**	NS

Figures followed by the same letters in a column are not significantly different from each other according to Tukey's HSD test.

Table 5 Initial and periodic amount of primary nutrients (Mg ha^{-1}) in decomposing litter of bamboo groves

Species	Initial			After 3 months			After 6 months		
	N	P	K	N	P	K	N	P	K
D g	0.048	0.004	0.023	0.043	0.003	0.016	0.037	0.002	0.012
B n	0.052	0.004	0.024	0.044	0.003	0.016	0.040	0.002	0.012
M b	0.056	0.005	0.030	0.049	0.004	0.014	0.043	0.003	0.013
SE_m	**0.004**	**0.0004**	**0.003**	**0.005**	**0.001**	**0.002**	**0.004**	**0.0003**	**0.001**
$CD_{p=0.05}$	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**

D g *Dendrocalamus giganteus,* B n *Bambusa nutans,* M b *Melocanna baccifera* al., 2003). However, a much higher litter production (15.4–20.3 Mg ha^{-1}) was reported from *Bambusa bamboo* plantations in Tamil Nadu (Shanmughavel et al., 2000). The annual return of nutrients in the order N > K > P was also observed in *B. cacharensis*, *B. Vulgaris* and *B. balcooa* plantations (Hariprasath et al., 2014; Nath & Das, 2011b). However, in the thorny bamboo plantation in Kerala's home gardens, the sequence was K > N > P (Kumar et al., 2005).

The amount of these primary nutrients decreased gradually as the decomposition progressed. Nutrients stocked in the bamboo biomass returned to the soil through litter fall and subsequent decomposition and leaching by percolating water (Polyakova & Billor, 2007). After litter decomposition, the release of these primary elements completes the cycle of plant litter elements within the soil–plant system (Rawat et al., 2010). Litter decomposition continues the mineralization processes, thus sustaining the bio-geochemical cycle for sustained clump growth, affecting hydrology, structure and functions of the bamboo groves (Muoghalu & Odiwe, 2011).

4.1 Biomass Accumulation and Partitioning

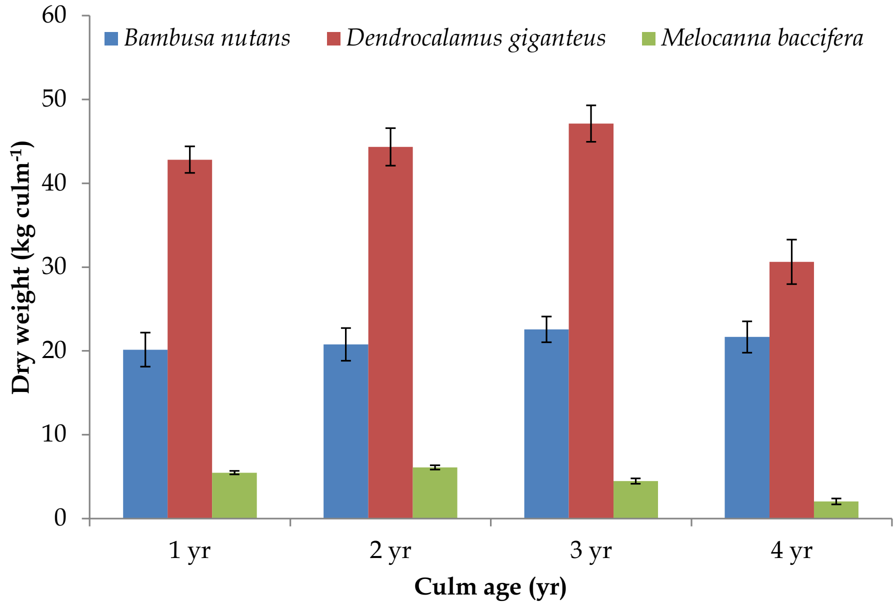
The biomass accumulation for different ages of the culms, above- and below-ground, is given in Table 6. The standing biomass of all the bamboo species varied significantly with the culm's age in the bamboo species but not always significant among different ages in their various plant organs. In general, all plant organs' biomass above and below-ground increased with age in all species except in *M. baccifera* where after the second year, the biomass decreased.

Table 6 Biomass accumulation and partitioning (Mg ha^{-1}) in bamboo groves

Y	C	CB	SB	LTB	AGB	RB	TPB
D. giganteus							
1	906b	36.14	1.10b	0.78b	38.02	15.61	53.63
2	1044b	43.47	1.30ab	1.36b	46.13	17.99	64.12
3	1144b	45.93	1.81ab	6.17a	53.90	19.40	73.30
4	1938a	44.81	2.79a	10.32a	57.92	22.01	79.92
SE_m	*116.89*	*4.85*	*0.47*	*1.55*	*6.14*	*2.28*	*8.41*
CD^*	*360.16*	*NS*	*1.44*	*4.79*	*NS*	*NS*	*NS*
GB	**5032**	**170.35**	**7.0**	**18.63**	**195.97**	**75.01**	**270.98**
B. nutans							
1	888	16.94	0.64	0.47b	18.05b	6.86b	24.91b
2	1025	19.91	0.84	0.44b	21.18ab	8.47ab	29.65ab
3	988	17.50	0.45	3.69a	21.64ab	8.00ab	29.64ab
4	1500	26.15	0.46	4.33a	30.94a	12.07a	43.01a
SE_m	*196.5*	*3.19*	*0.13*	*0.43*	*3.37*	*1.29*	*4.67*
CD^*	*NS*	*NS*	*NS*	*1.34*	*10.39*	*3.99*	*14.38*
GB	**4401**	**80.5**	**2.39**	**8.93**	**91.81**	**35.4**	**127.21**
M. baccifera							
1	569	2.67ab	0.20	0.33b	3.19b	1.34ab	4.53b
2	675	3.10a	0.08	0.93a	4.11a	1.64a	5.75a
3	656	2.21b	0.25	0.48ab	2.94b	1.09b	4.02b
4	725	0.98c	0.15	0.32b	1.45c	0.56c	2.01c
SE_m	*55.14*	*0.20*	*0.06*	*0.15*	*0.28*	*0.11*	*0.39*
CD^*	*NS*	*0.60*	*NS*	*0.47*	*0.87*	*0.34*	*1.20*
GB	**2625**	**8.96**	**0.68**	**2.06**	**11.69**	**4.63**	**16.32**

Y year, *C* number of culms ha^{-1}, *CB* culm biomass Mg ha^{-1}, *SB* sheath biomass Mg ha^{-1}, *LTB* leaf and twig biomass Mg ha^{-1}, *AGB* above ground biomass Mg ha^{-1}, *RB* root biomass Mg ha^{-1}, *TPB* total plant biomass Mg ha^{-1}, *GB* grove biomass Mg ha^{-1}; $^*P = 0.05$. Figures followed by the same letters in a column are not significantly different from each other according to Tukey's HSD test.

Fig. 3 Changes in dry culm mass with age in three-bamboo species



However, no such trend was observed in the case of the number of culms with increasing age. For all the age classes, *D. giganteus* had higher biomass of all the plant organs above and below-ground than *B. nutans* and *M. baccifera*. However, considering the dry weight, all three species' biomass increased with the increase in culm age up to the third year and declined in the fourth year of culm age (Fig. 3).

The total standing grove biomass of *D. giganteus*, *B. nutans* and *M. baccifera* was estimated at 270.97, 127.21 and 16.31 Mg ha^{-1}, respectively (Table 6). The contribution of above-ground biomass (AGB) to total standing grove biomass was similar for all the species, i.e. in *D. giganteus*, *B. nutans* and *M. baccifera*, the contribution was 72.32%, 72.17% and 71.63%, respectively. In comparison, the rest (27.68%, 27.83% and 28.37%, respectively) was contributed by the roots or below-ground biomass (BGB). Thus, no proportional change either in AGB or BGB to total plant biomass was observed in all three-bamboo species.

AGB contributed about 72% of the total standing biomass for all the ages of all the species, while the roots contributed 28%. The AGB and BGB of the bamboo were approximately in the ratio 3:1 (Singh et al., 2006; Seethalakshmi et al., 2009). Culm is the major contributor of both AGB and total plant biomass in all three-bamboo species. *D. giganteus* culms contributed 86.93% and 62.86% towards AGB and total standing biomass, respectively, while in *B. nutans* it was 87.68% and 63.28%, respectively. However, in *M. baccifera*, culm contributed 76.65% towards AGB and 54.90% towards total standing biomass. A study from Barak valley, Assam, also estimated similar AGB of the bamboo stands with 121.51 Mg ha^{-1}, of which and 86% of this biomass was contributed by culms, 10% by branches and 4% by leaves (Nath et al., 2009).

5 Appropriateness of Simple Power-Law Models

The power-law model's performance with following two other models involving D alone and H alone was compared.

$$\text{Model1}: \ln(Y) = \ln(\alpha) + \beta \ln(D)$$
$$\text{Model2}: \ln(Y) = \ln(\alpha) + \beta \ln(H)$$

where α is the normalization (proportionality) constant, β is the exponent, D is the culm diameter and H is the culm height.

Based on the higher R^2 and adj R^2, and lower AIC and HQC, Model 1 was more appropriate for *B. nutans* and *D. giganteus*, where Model 2 was suitable for *M. baccifera* (Table 7).

Table 7 Parameter estimates of the various biomass models and goodness of fit statistics for three-bamboo species

Species	Model	Intercept(a)	Slope (b)	R^2	Adjusted R^2	AIC
D. giganteus	1	**0.73 (0.16)**	**0.95 (0.18)**	**0.42**	**0.40**	**−2.27**
	2	0.30 (0.29)	0.42 (0.09)	0.34	0.32	−2.14
B. nutans	1	**0.26 (0.186)**	**1.31 (0.232)**	**0.46**	**0.47**	**−2.81**
	2	0.18 (0.241)	0.41 (0.087)	0.36	0.35	−2.66
M. baccifera	1	−0.24 (0.12)	1.42 (0.21)	0.54	0.53	−0.87
	2	**−0.61 (0.17)**	**0.59 (0.08)**	**0.58**	**0.57**	**−0.96**

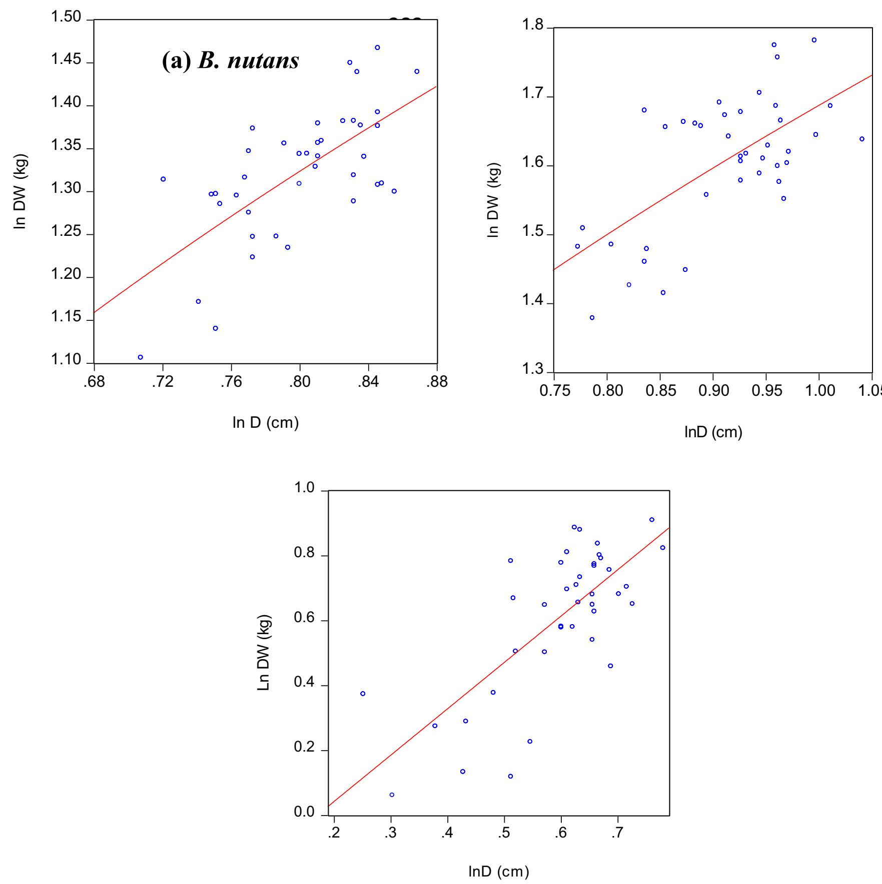


Fig. 4 Allometric relationship between above ground biomass (AGB) and diameter at breast height (*D*) of three different bamboo species (**a**–**c**)

The allometric relationship between above ground biomass (AGB) and diameter at breast height (*D*) exhibited a strong relationship suggesting the diameter of the culm can be used as an independent variable for above ground estimation in the three species (Fig. 4).

Similar *H*–*D* relationships and allometric scaling between (AGB), culm height (*H*) and diameter at breast height (*D*) were examined for *Schizostachyum dullooa*, *Pseudostachyum polymorphum* and *Melocanna baccifera* using various models (Singnar et al., 2017).The analysis found that *H*, *D* and AGB are allometrically related in the different aged bamboo culms. Allometric equation $Y = -3225.8 + 1730.4$ dbh developed ($R^2 = 0.83$ and *Y* is the total biomass per clump) for thorny bamboo (*Bambusa bamboos*) in the homegardens of Kerala had high R^2, which reasonably gave a better prediction of culm number per clump and standing stock of biomass values justified (Kumar et al., 2005).

Table 8 Standing biomass carbon and partitioning (Mg ha^{-1}) in bamboo groves

Y	CB	SB	LTB	AGB	RB	TPB
Dendrocalamus giganteus						
1	18.07	0.55_b	0.39_b	19.02	7.81	26.83
2	21.74	$0.65a_b$	0.68_b	23.07	9.00	32.07
3	22.97	$1.03a_b$	3.09_a	26.96	9.70	36.66
4	22.41	1.40_a	5.16_a	28.96	11.01	39.97
SE_m	*2.42*	*0.23*	*0.78*	*3.07*	*1.14*	*4.21*
$CD_{p = 0.05}$	*NS*	*0.72*	*2.39*	*NS*	*NS*	*NS*
GBC	**85.19**	**3.63**	**9.32**	**98.01**	**37.52**	**135.53**
Bambusa nutans						
1	8.47	0.32	0.24_b	9.03_b	3.44_b	12.47_b
2	9.96	0.42	0.22_b	10.59_{ab}	4.24_{ab}	14.83_{ab}
3	8.75	0.23	1.85_a	10.82_{ab}	4.01_{ab}	14.83_{ab}
4	13.07	0.23	2.17_a	15.48_a	6.04_a	21.52_a
SE_m	*1.59*	*0.06*	*0.22*	*1.69*	*0.65*	*2.33*
$CD_{P = 0.05}$	*NS*	*NS*	*0.67*	*5.19*	*1.99*	*7.19*
GBC	**40.25**	**1.2**	**4.48**	**45.92**	**17.73**	**63.65**
Melocanna baccifera						
1	1.34_{ab}	0.10	0.17_b	1.61_b	0.67_{ab}	2.28_b
2	1.55_a	0.04	0.47_a	2.06_a	0.83_a	2.89_a
3	1.11_b	0.11	0.24_{ab}	1.46_b	0.55_b	2.01_b
4	0.49_c	0.05	0.16_b	0.70_c	0.28_c	0.98_c
SE_m	*0.10*	*0.03*	*0.08*	*0.14*	*0.06*	*0.20*
$CD_{p = 0.05}$	*0.30*	*NS*	*0.24*	*0.43*	*0.17*	*0.60*
GBC	**4.49**	**0.3**	**1.04**	**5.83**	**2.33**	**8.16**

Y year, *CC* culm carbon Mg ha^{-1}, *SC* sheath carbon Mg ha^{-1}, *LTC* leaf and twig carbon Mg ha^{-1}, *AGBC* above ground biomass carbon Mg ha^{-1}, *RC* root carbon Mg ha^{-1}, *TPC* total plant carbon Mg ha^{-1}, *GBC* grove biomass carbon Mg ha^{-1}. Figures followed by the same letters in a column are not significantly different from each other according to Tukey's HSD test.

5.1 Bamboo Biomass Carbon Stock

The biomass carbon for different ages of the culms, above- and below-ground, is given in Table 8. All bamboo species' standing biomass carbon storage varied significantly with the culm's age. In general, the carbon stocked by the three-bamboo species' plant organs above and below-ground increased with age, but in *M. baccifera*, the carbon stock decreased after the second year. The total standing bamboo grove carbon stock of *D. giganteus*, *B. nutans* and *M. baccifera* was estimated at 135.53, 63.65, and 8.16 Mg ha^{-1}, respectively (Table 8). Many studies have also similarly reported the carbon storage potential of different species of bamboos with AGB carbon storage in the range of 16–128 Mg ha^{-1}, while BGB carbon storage in the range of 8–64 Mg ha^{-1} (Devi et al., 2018; Nath et al., 2018; Pongon et al., 2016; Singh et al., 2006; Singnar et al., 2017; Thokchom & Yadava, 2017; Yuen et al., 2017). The contribution of AGB carbon to total standing grove biomass carbon was similar for all the species, i.e. the contribution was about 72%, while the roots contributed the rest.

No proportional change either in AGB carbon or BGB carbon to total plant biomass carbon was observed in all the three-bamboo species with an increase in age of the culm. Culm is the major contributor of both AGB carbon and total plant biomass in all three-bamboo species at all ages. The culms are the major contributor of carbon storage, contributing 58–90% of the grove's total carbon (Nath & Das, 2011a, 2012; Nath et al., 2009; Pongon et al., 2016; Thokchom & Yadava, 2017). It was also observed that with the increasing age of the culms,

Table 9 Ecosystem carbon stock (Mg ha^{-1}) of three species of bamboo

Species	Biomass C	Litter C	SOC stock (0–60 cm)	Ecosystem C
Dendrocalamus giganteus	135.53_a	2.76	24.99_b	163.28_a
Bambusa nutans	63.65_b	2.91	26.11_b	92.67_b
Melocanna baccifera	8.16_c	3.06	33.23_a	44.46_c
SE_m	**7.24**	**0.29**	**0.36**	**7.89**
$CD_{p=0.05}$	**23.08**	**NS**	**1.14**	**25.23**

Figures followed by the same letters in a column are not significantly different from each other according to Tukey's HSD test.

their contribution towards both AGB carbon and total standing biomass carbon decreased.

Most of the stored carbon in stands i.e. 58–73% was contributed by current and one-year-old culm (Nath & Das, 2012). The contribution of culms towards AGB carbon and total standing biomass carbon was much lesser in *M. baccifera* than the other two bamboo species at all age classes. The carbon stock of the three species of bamboos of the present study is low compared to earlier studies because of regular selective felling. Still, it is a permanent stock as new culms are produced regularly and thus an efficient system for carbon sequestration (Nath & Das, 2011a). Moreover, variation in species, size, stem/culm density, stand age and environmental conditions influence biomass production, resource capture and productivity, which are finally reflected in the carbon storage by vegetation (Fotis et al., 2018; Li et al., 2019). Environmental conditions directly affect carbon storage regulating nutrient and water availability (Jucker et al., 2016).

6 Bamboo Ecosystem Carbon Stock

Bamboo ecosystem carbon stock comprises bamboo standing biomass carbon, soil carbon up to 60-cm depth and litter carbon (Table 9). The ecosystem carbon stock of *D. giganteus* is significantly (163.28 Mg ha^{-1}) higher than the other two species because of its significantly higher biomass carbon accumulation.

Biomass carbon storage of 8.1–135.53 Mg ha^{-1} and ecosystem carbon stock of 44.46–163.28 Mg ha^{-1} under a bamboo-based land-use system indicate that the bamboo species are capable of trading carbon under CDM and REDD + schemes. This amount of biomass carbon storage and ecosystem carbon stock is comparable with agroforestry and forest ecosystems. These bamboos can be a good option for carbon farming and carbon trading role in climate change adaptation and mitigation apart from its contribution in social and economic contributions to the rural life of the region (Lobovikov et al., 2012; Song et al., 2011; Yen, 2015; Yen & Wang, 2013). In the Terai region of West Bengal, farmers manage bamboo either in the traditional agroforestry system or in pure stands adjoining their home gardens called 'bamboo grove' (Nath & Das, 2011a). Residents selectively harvest bamboos for livelihood purposes, which have no negative impact on bamboo's productivity and, therefore, a sustainable practice (Hoogendoorn & Benton, 2014). It has been recommended to consider sustainable biomass removal in future REDD + strategies to realize bamboo's potential to combat deforestation (Hein & van der Meer, 2012). Despite selective felling, biomass and carbon stock in bamboo are considered permanent as new culms are added in a clump every year (Nath & Das, 2011a).

7 Conclusions

The soil pH, moisture and electrical conductivity under different bamboo groves of three species varied significantly. However, moisture and electrical conductivity exhibited inconsistency with soil depth. Availability of nitrogen, phosphorus and potassium in the soils of *the Melocanna baccifera* grove was higher than *Bambusa nutans* and *Dendrocalamus giganteus* groves. The amount of soil organic carbon (SOC- oxidizable) in the bamboo groves at different depths varied significantly among the three-bamboo species. Consequently, the highest litter production by the *M. baccifera* grove, the amount of SOC estimated in the grove was also highest. The litter decomposition was slow initially, which gradually increased with time and within nine months entire litter mass of the bamboo groves decomposed. The standing biomass of the three-bamboo species varied significantly with the age of the culm. Biomass carbon storage (8.1–135.53 Mg ha^{-1}) and ecosystem carbon stock (44.46–163.28 Mg ha^{-1}) estimated bamboo species is comparable to that under the agroforestry and forest ecosystems worldwide. Therefore, bamboos from the Terai region can be considered for carbon farming and trading while offering a viable climate change adaptation and mitigation strategy.

Additionally, commercialization of the traditional bamboo crafts with value addition may improve rural folks' livelihood through income generation. This can be achieved by popularizing and commercializing bamboo crafts and products through value addition, which will also improve the livelihood of rural folks through income generation. Bamboo artefacts and crafts are durable, and because of their considerable residence time, these uses of bamboo have negative feedback on climate change.

Data Availability All data generated or analyzed in this study has been included in this article. No additional data is associated with this study.

Declarations

Conflict of Interest The authors declare no competing interest.

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