Forest Types, Biomass and Carbon Dynamics in the Northeastern States of India: A Comprehensive Review

Pooja Dasgupta, Dhruba Jyoti Das

ABSTRACT

Forest ecosystems play a vital role in sequestering carbon, primarily functioning as terrestrial carbon sinks that significantly help reduce atmospheric carbon dioxide levels. The north-eastern states of India (comprising an area of approximately 168,903 km²) collectively account for a substantial portion of the country's forest resources (23.61% of the total forest cover). The present paper attempts to explore the forest types, patterns of biomass distribution, and carbon storage potential across Northeast India, emphasizing on their ecological importance and conservation needs. It also examines the destructive, non-destructive, and remote sensing & GIS-based biomass estimation techniques employed by various researchers to identify existing research gaps. This amalgamated data from various methodologies, provides an all-inclusive appraisal of biomass carbon across the eight North-eastern states of India.

Keywords Aboveground biomass, Litter, Carbon stock, Allometric equations, Remote sensing & GIS.

INTRODUCTION

Climate regulation is a fundamental ecosystem service provided by forest ecosystems, primarily due to their role as terrestrial carbon sinks. Forests sequester carbon in various forms, significantly contributing to the reduction of atmospheric carbon dioxide levels. In ecological terms, carbon stock refers to the total amount of carbon stored within an ecosystem, primarily distributed in biomass and soil. Biomass carbon is further categorized into four distinct pools: Aboveground biomass carbon, belowground biomass carbon, deadwood, and litter (IPCC 2003). Together, these pools determine the overall carbon sequestration capacity of the forest ecosystems.

In India, the northeastern states collectively account for a substantial portion of the country's forest resources, covering an area of approximately 168,903 km², which constitutes 23.61% of the total forest cover (FSI 2023). Among these states, Arunachal Pradesh boasts the largest forest cover in India, spanning 65,882 km², making it the leading State in

Pooja Dasgupta[1]*, Dhruba Jyoti Das[2]

[1]PhD Scholar, [2]Scientist-F

[1]Forest Ecology and Environment, ICFRE-Rain Forest Research Institute, Jorhat 785010, Assam, India

[2]Forest Ecology and Climate Change Division, ICFRE- Rain Forest Research Institute, Jorhat 785010, Assam, India

Email: poojadasgupta.tsk@gmail.com
*Corresponding author

Forest carbon stock, totalling 1,021,160,000 Mg. This emphasizes the significant role of Northeastern forests in national and global carbon dynamics, highlighting the need for preserving forest integrity in Northeast India. The predominance of aboveground biomass (37.44 Mg ha^{-1}) underscores the significance of species composition and canopy density in carbon storage, while belowground biomass (10.18 Mg ha^{-1}) highlights the role of root systems in long-term carbon sequestration. Deadwood (0.65 Mg ha^{-1}) and litter (1.75 Mg ha^{-1}) contribute relatively smaller fractions, yet they play a crucial role in nutrient cycling and soil carbon enrichment. FSI (2023) estimates the region's average biomass carbon stock at 50.01 Mg ha^{-1}, which is slightly higher than the national average of 45.77 Mg ha^{-1}. Among the Northeastern states, Sikkim records the highest per hectare biomass carbon stock at 78.15 Mg ha^{-1}, while Mizoram has the lowest at 39.89 Mg ha^{-1}. Despite this regional variation, the overall biomass carbon stock in Northeast India remains lower than the global forest carbon stock average of 163.10 Mg ha^{-1} (FAO 2020). The relatively lower biomass carbon stock in the region compared to the global average suggests potential areas for enhancing carbon sequestration through sustainable forest management practices.

Strategies such as afforestation, reforestation, and agroforestry can be instrumental in increasing biomass productivity and improving the overall carbon sink capacity of these forests. The variation in biomass carbon stock across northeastern states can be attributed to multiple ecological and anthropogenic factors, including forest type, species composition, elevation gradients, land-use changes, precipitation patterns, soil fertility and forest management practices. For instance, the high per hectare carbon stock in Sikkim may be linked to its dense, well-preserved forest ecosystems and favorable climatic conditions (Ravindranath *et al.* 2012) that support high biomass accumulation. Conversely, Mizoram's lower carbon stock per hectare could be associated with shifting cultivation practices (Sati and Rinawma 2014) and landscape disturbances that reduce overall carbon retention. Given these disparities, region-specific conservation policies are crucial to enhancing carbon sequestration efficiency. For example, states with lower per hectare carbon stocks, such as Mizoram,

could benefit from targeted afforestation and soil conservation programs, while states like Sikkim, with higher carbon density, may focus on maintaining and protecting existing forest resources. As climate change accelerates, maintaining and enhancing forest carbon sinks in this biodiversity-rich region will be critical for mitigating carbon emissions and supporting ecosystem resilience.

Types of forests in North East India

According to climatic, physiognomic, edaphic and other relevant parameters such as species composition, phenology, topography, altitude, aspect, and biotic factors, all six major forest types are present in the eight states that make up North East India (Table 1). Northeastern India is home to thirteen of the sixteen groupings (excluding Tropical Thorn Forests, Tropical Dry Evergreen Forests, and Subtropical Dry Evergreen Forests) and other subgroups with distinctive characteristics.
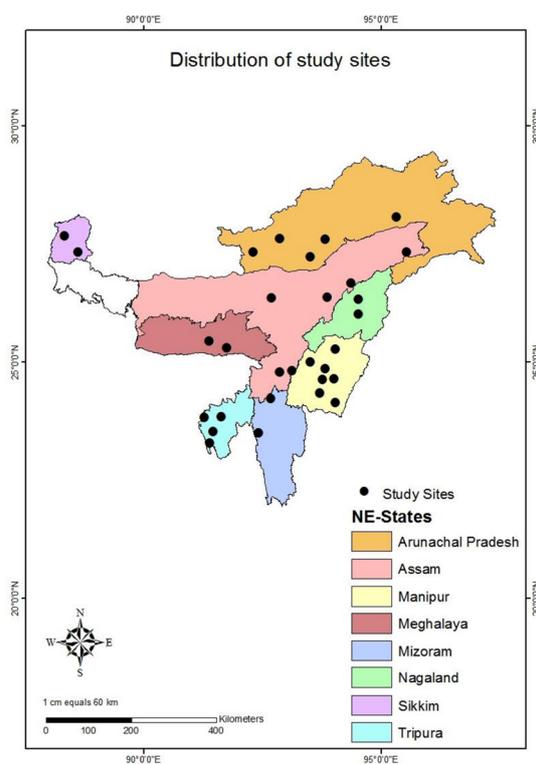

Fig. 1. Geographic distribution of study sites from the reviewed articles.

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Table 1. The major forest types in the Northeastern states of India (Champion and Seth 1968, ICFRE 2013).

States	Types	Groups	Sub-groups
Arunachal Pradesh	Moist Tropical Forests (I), Montane Subtropical Forests (III), Montane Temperate Forests (IV), Sub-Alpine Forests (V), Alpine Scrub (VI)	Tropical Wet Evergreen Forests (1), Tropical Semi-Evergreen Forests (2), Tropical Moist Deciduous Forests (3), Subtropical Broadleaved Hill Forests (8), Subtropical Pine Forests (9), Himalayan Moist Temperate Forests (12), Himalayan Dry Temperate Forests – Eastern types (13 (ii)), Sub-Alpine Forests (14), Moist Alpine Scrub (15) Dry Alpine Scrub (16)	1B/C2a, 2S1, 2B/C1a, 2B/C1b, 2B/1S1, 2B/2S2, 2/2S1, 3C/2S2, 3/1S2(b), 8B/C1, 9/C2, 12/C1a, 12/C3a, 12/DS1, 12/E1, 12/2S1, 13(ii)/E1, 14/C2, 15/C1, 16/C1
Assam	Moist Tropical Forests (I), Dry Tropical Forests (II), Montane Subtropical Forests (III)	Tropical Wet Evergreen Forests (1), Tropical Semi-Evergreen Forests (2), Tropical Moist Deciduous Forests (3), Littoral and Swamp Forests (4), Tropical Dry Deciduous Forests (5), Subtropical Pine Forests (9)	1B/C2a, 1B/C2b, 1B/C3, 2S1, 2B/C1a, 2B/C1b, 2B/1S1, 2B/2S2, 2B/2S3, 2B/C2, 2/2S1, 3C/C1a(ii), 3C/C1b(i), 3C/C2d(iv), 3C/C3b, 3C/2S1, 3/1S2a, 4D/SS4, 4D/SS5, 5/1S2, 9/C2
Manipur	Moist Tropical Forests (I), Montane Subtropical Forests (III),	Tropical Semi-Evergreen Forests (2), Tropical Moist Deciduous Forests (3), Subtropical Broadleaved Hill Forests (8), Subtropical Pine Forests (9), Montane Wet Temperate Forests (11)	2B/C1b, 2/2S1, 3C/C3b, 8B/C1, 8B/C2, 8B/2S1, 9/C2, 9/DS1, 11B/C1b
Meghalaya	Moist Tropical Forests (I), Montane Subtropical Forests (III), Montane Temperate Forests (IV)	Tropical Wet Evergreen Forests (1), Tropical Semi-Evergreen Forests (2), Tropical Moist Deciduous Forests (3), Subtropical Broadleaved Hill Forests (8), Subtropical Pine Forests (9)	1B/C3, 2S1, 2/2S1, 3C/C1a(ii), 3C/C3b, 8B/C2, 8B/2S1, 9/C2
Mizoram	Moist Tropical Forests (I), Montane Subtropical Forests (III)	Tropical Semi-Evergreen Forests (2), Tropical Moist Deciduous Forests (3), Subtropical Broadleaved Hill Forests (8), Subtropical Pine Forests (9)	2B/2S1, 2B/C2, 2/2S1 3C/C3b, 8B/C1, 9/C2
Nagaland	Moist Tropical Forests (I), Montane Subtropical Forests (III), Montane Temperate Forests (IV)	Tropical Wet Evergreen Forests (1), Tropical Semi-Evergreen Forests (2), Tropical Moist Deciduous Forests (3), Subtropical Broadleaved Hill Forests (8), Subtropical Pine Forests (9), Montane Wet Temperate Forests (11)	1B/C1, 2B/2S2, 2B/C2, 2/2S1, 3C/C3b, 8B/2S1, 9/C2, 11B/C2
Sikkim	Moist Tropical Forests (I), Montane Subtropical Forests (III), Montane Temperate Forests (IV), Sub-Alpine Forests (V)	Tropical Moist Deciduous Forests (3), Subtropical Broadleaved Hill Forests (8), Montane Wet Temperate Forests (11), Himalayan Moist Temperate Forests (12), Himalayan Dry Temperate Forests – Eastern types (13 (ii)), Sub-Alpine Forests (14), Moist Alpine Scrub (15)	3C/C1a (i), 3C/C3b, 8B/C1, 11B/C1b, 12/C3a, 13 (ii) / C6, 14/C2, 15/C1, 15/E1, 15/E2
Tripura	Moist Tropical Forests (I)	Tropical Semi-Evergreen Forests (2), Tropical Moist Deciduous Forests (3)	2/2S1, 3C/C1b(ii), 3C/C3b, 3/1S1

NB: 1B-Northern tropical wet evergreen forests, C1- Assam Valley tropical wet evergreen forest (*Dipterocarpus*), C2-Upper Assam Valley tropical evergreen forest a) Kayea forest, b) Mesua forest, C3- Cachar tropical evergreen forest, 2S1- Pioneer Euphorbiaceous scrub,

2B- Northern tropical semi-evergreen forests, C1- Assam Valley semi-evergreen forest a) Assam alluvial plains semi evergreen forest b) Eastern submontane semi-evergreen forest, 1S1- Sub-Himalayan light alluvial semi-evergreen forest, 2S1- Pioneer Euphorbiaceous scrub, 2S2- Eastern alluvial secondary semi-evergreen forest, 2S3- Sub-Himalayan secondary wet mixed forest, C2- Cachar semi-evergreen forest, 2/2S1- Secondary moist bamboo brakes, 3C-North Indian moist deciduous forests, C1- Very moist sal-bearing forest a) Eastern bill sal forest i) East Himalayan sal, ii) Khasi hill sal, b) Eastern *bhabar* sal forest, i) East Himalayan upper *bhabar* sal, ii) East Himalayan lower *bhabar* sal C2- Moist sal-bearing forest d) Moist plains sal forest iv) App. Kamrup sal, C3- Moist mixed deciduous forest (without sal) b) East Himalayan moist mixed deciduous forest, 2S1- Northern secondary moist mixed deciduous forest, 2S2-Secondary Euphorbiaceous scrub, 3/1S1- Low alluvial savannah woodland (*Salmalia-Albizzia*) 3/1S2- Eastern hoolock forest (*Terminalia myriocarpa*) a) *Terminalia-Lagerstroemia* b)*Terminalia-Duabanga*, 4D- Tropical seasonal swamp forests SS4-Eastern seasonal swamp low forest (*Cephalanthus*), SS5- Eastern *Dillenia* swamp forest, 5/1S2- Khair-sissu forest, 8B- Northern subtropical broadleaved wet hill forests C1-East Himalayan subtropical wet hill forest, C2- *Khasi* subtropical wet hill forest, 2S1- Assam subtropical pine forest, 9/DS1- Himalayan subtropical scrub, C2- Assam subtropical pine forests, 11B- Northern montane wet temperate forests C1- East Himalayan wet temperate forests b) *Buk* oak forest C2- Naga hills wet temperate forest, 12/C1- Lower Western Himalayan temperate forest a) Ban oak forest (*Q. Incana*), 12/C3- East Himalayan moist temperate forest a) East Himalayan mixed coniferous forest, 12/DS1- Montane bamboo brakes, 12/E1- Cypress forest, 12/2S1- Low-level blue pine forest, 13 (ii)- Eastern types C6- East Himalayan dry temperate coniferous forest, E1- Larch forest (*L. griffithiana*), 14/C2- East Himalayan sub-alpine birch/fir forest, 15/C1- Birch/ *Rhododendron scrub* forest, E1- Dwarf *Rhododendron scrub*, E2- Dwarf juniper scrub, 16/C1- Dry alpine scrub.

Table 2. Some of the aboveground biomass allometric equations of trees used in the study. (D=diameter at breast height, H=height, δ, ρ =specific gravity).

Aboveground biomass equation	Studies in NE	Reference
AGB = 21.297-6.953(D)+0.740(D^2)	Borah *et al*. (2013), Waikhom *et al.* (2017)	Brown (1997)
AGB = 13.2579−(4.8945D) +0.6713D	Majumdar *et al.* (2016), Waikhom *et al.* (2017)	Brown *et al.* (1989)
AGB = 0.0509*ρ*D^2*H	Borah *et al.* (2015), Chaudhury and Upadhaya (2016), Mir *et al*. (2021)	Chambers *et al.* (2001)
AGB = 0.0673 * (ρ*D^2*H)0.976	Singh *et al.* (2018), Wapongnungsang *et al.* (2021)	Chave *et al.* (2005)
AGB = 0.32 (D^2*H*δ) 0.75 ×1.34	Das *et al*. (2021), Gogoi *et al.* (2020), Ao *et al.* (2023)	Nath *et al.* (2019)

Table 3. Estimation of belowground biomass using various allometric equations.

Belowground biomass equation	Studies in NE	Reference
BGB=20%*AGB	Mihriemate *et al.* (2020)	Achard *et al.* (2002), Ramankutty *et al.* (2007)
BGB = exp {−1.059 + 0.884 × ln (AGB) + 0.284}	Baidya *et al.* (2024), Chaudhury and Upadhaya (2016), Mir *et al.* (2021), Singh *et al.* (2018), Ao *et al.* (2023), Rai *et al* (2018)	Cairns *et al.* (1997)
BGB=29% *AGB	Bordoloi *et al.* (2019)	IPCC (2005)
BGB=24% *AGB	Gogoi *et al.* (2020)	Mokany *et al.* (2006)
BGB=26% *AGB	Das *et al*.(2020), Devi *et al*.(2021)	IPCC (2003), Ravindranath and Ostwald (2008)

Geographic distribution of study sites

The map, prepared using ArcMap 10.3.1, illustrates the geographic distribution of study sites from the articles reviewed in this paper (Fig. 1). By visualizing the spatial extent of existing research, this map highlights regional patterns, gaps and concentrations in study locations. It provides a comprehensive overview of where research efforts have been focused, offering insights into geographic trends and potential areas for future study. Understanding the distribution of study sites is crucial for identifying biases in research coverage and ensuring a more balanced and representative body of knowledge.

Methods employed for estimation of biomass

Accurate biomass estimation is essential for assessing forest productivity and monitoring carbon pools. However, no single reliable technique has been developed to achieve precise biomass estimation, leading to variations in results when different methodologies
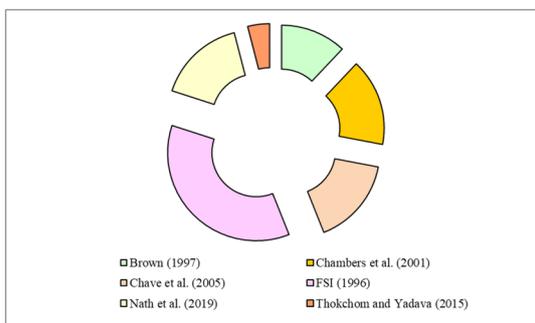
Fig. 2. Application of volume equations and various allometric equations for biomass estimation in studies (2013-2024) across North East India.

are applied. Biomass estimation techniques can be broadly categorized into destructive, non-destructive and remote sensing & geographic information system (GIS)-based approaches.

The destructive method, commonly referred to as the harvest method, involves cutting, drying and weighing plant components to determine biomass. While this method provides direct and accurate measurements, it is labor-intensive, time-consuming, and non-feasible for large-scale applications due to its non-sustainable nature. Harvest method is used to estimate the biomass of herb and litter in accordance with Misra (1968) (cited in Singh *et al.* (2018), Das *et al.* (2021) and Ao *et al.* (2023)).

The non-destructive method estimates biomass using measurable parameters such as girth at breast height (GBH), tree height, tree volume and wood density. These measurements are used in allometric equations to derive biomass values. Various allometric equations have been applied to estimate the aboveground biomass of trees in the Northeastern States (Table 2). Additionally, studies have employed tree volume computation methods based on formulae developed by Pressler (1865) and the Forest Survey of India (FSI 1996), with the latter being the most preferred method in studies from Northeast India (Fig. 2). The calculation of bole biomass involves multiplying volume with wood specific gravity, with values sourced from FAO (1997), FSI (1996), and multiple other studies (Gupta *et al.* 2017, Hidayat 1994, Kanawjia *et al.* 2013, Limaye & Sen 1956, Rajput *et al.* 1996, Williamson & Wiemann 2010, Zanne *et al.* 2009) in the studies of Das *et al.* (2016), Thokchom & Yadava (2017), Banik *et al.* (2018), Giri *et al.* (2019), Mihriemate *et al.* (2020) and Devi *et al.* (2021). Biomass Expansion Factor (BEF) has been used to convert bole biomass into total aboveground biomass. Studies have applied BEF values of 1.59 (Haripriya 2000), 1.58 (Kaul *et al.* 2009) and 0.8 (IPCC 2006) in the works of Banik *et al.* (2018), Giri *et al.* (2019) and Devi *et al.* (2021).

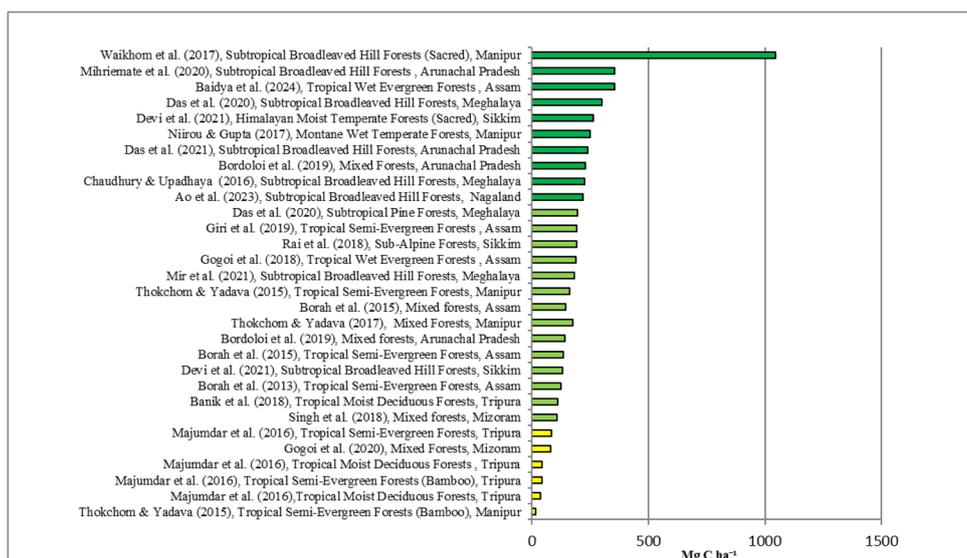Specific methodologies have been employed for

Fig. 3. Estimates of aboveground biomass from selected studies (2013-2024) in North East India.
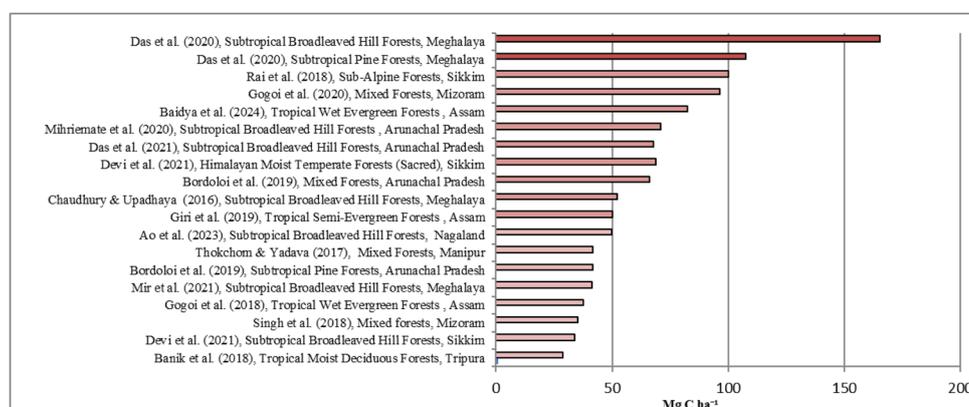
Fig. 4. Estimates of belowground biomass from selected studies (2016-2024) in North East India.

biomass estimation of different plant groups, including bamboo, bananas, lianas, palms and others. The aboveground biomass for bamboos was based on the equations of Thokchom and Yadava (2015), Singnar *et al.* (2017) (cited in Gogoi *et al.* (2020)) and Das (2012). Following the methodology employed in Gogoi *et al.* (2020) and Singh *et al.* (2018), the biomass of bananas and lianas were evaluated using the allometric equations created by Hairiah *et al.* (2011) and Fordjour and Rahmad (2013). Also, Schnitzer *et al.* (2006), as cited in Chaudhury and Upadhaya (2016), were utilized to estimate liana biomass. Palm biomass and arecanut were estimated employing the equations proposed by Brown (1997), as cited in Singh *et al.* (2018), while oil palm biomass was assessed using the approach outlined by Khalid *et al.* (1999), also referenced in Singh *et al.* (2018).

Shrub and tree sapling biomass was estimated using allometric equation by Ali *et al.* (2015), applied in Singh *et al.* (2018), Gogoi *et al.* (2020) and Ao *et al.* (2023). Belowground biomass was estimated using allometric equations based on varying percentages of aboveground biomass (Table 3). Deadwood biomass were derived using methodologies from Clark *et al.* (2002), Cros & Lopez (2009) and Pfeifer *et al.* (2015), as cited in Singh *et al.* (2018) and Gogoi *et al.* (2020). Biomass carbon content was estimated at different proportions, including 45%, 47%, 47.4%, 50% and 55% of total biomass (Table 4).

Satellite-based modelling techniques have been increasingly applied to estimate biomass and carbon stocks in Northeast India. These studies involve converting satellite-derived Digital Number (DN) values into reflectance values, followed by the computation of vegetation indices such as Difference Vegetation Index (DVI), Normalized Difference Vegetation Index (NDVI), Transformed Vegetation Index (TVI), Soil-Adjusted Vegetation Index (SAVI), Atmospheric Resistance Vegetation Index (ARVI), Enhanced Vegetation Index (EVI) (Bordoloi *et al.* 2019, Das *et al.* 2020, Das *et al.* 2021). Ground-measured biomass carbon stock per unit area is correlated with satellite-derived indices to identify the best-fit model for biomass estimation. The SAVI-based model was preferred for total biomass estimation due to its ability to minimize soil brightness effects, while ARVI was utilized by Das *et al.* (2021) to reduce atmospheric scattering effects. Additionally, Das *et al.* (2016) emphasized the importance of surface-area-based analysis, particularly in hilly terrains, for improving biomass estimation accuracy.

While destructive and non-destructive methods remain fundamental approaches, advancements
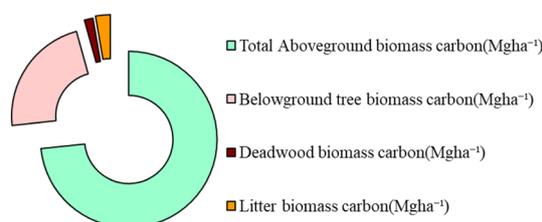

Fig. 5. Estimated mean total biomass carbon (2013-2023) in North East India based on the reviewed studies.

Table 4. Estimation of biomass carbon using various percentages of biomass.

Carbon stock formula	Studies in NE	Reference
C= 45% *B	Niirou and Gupta (2017) studied montane hill forests in Manipur, while Rai *et al.* (2018) examined subalpine conifer-mixed forests in Sikkim	Negi *et al.* (2003) and Sharma *et al.* (2010) studied conifer and broad-leaved forests in Uttarakhand, India. Negi *et al*. (2003) found conifers more efficient in carbon sequestration than deciduous, evergreen, and bamboo species, with carbon content estimated at 46% for conifers and 45% for broad-leaved forests. Manhas *et al*. (2006) assessed carbon stocks across Indian forests. excluding UTs like Delhi, Chandigarh, Lakshadweep and Pondicherry, using a 45% biomass-to-carbon ratio
C= 47% *B	Banik *et al.* (2018) studied forests in Sadar, Udaipur, and Teliamura, Tripura. Mihriemate *et al.* (2020) researched the Pasighat Forest Division, Arunachal Pradesh. Gogoi *et al.* (2020) studied the Dampa Tiger Reserve, Mizoram. Devi *et al.* (2021) focused on sacred groves in Enchey Monastery and Dzongu, North Sikkim. Baidya *et al.* (2024) examined the Soraipung Range in Dihing Patkai National Park, Assam.	IPCC (2000, 2006) analyzed forests in multiple countries, including the USA, Canada, Brazil, Norway, Russia, Spain, Hungary, Sudan, Malawi, India, Japan and Australia. The study established a standardized default biomass carbon fraction of 47% as a benchmark for estimating carbon stocks and fluxes worldwide
C= 47.4% *B	Chaudhury and Upadhaya (2016) studied subtropical forests in Cherrapunjee, Meghalaya	Martin and Thomas (2011) studied tropical forests in central Panama
C= 50% *B	Borah *et al.* (2013, 2015) and Giri *et al.* (2019) studied tropical forests in Assam's Cachar, Jorhat, Nagaon and Karbi Anglong districts. Das *et al.* (2016), Majumdar *et al.* (2016) and Waikhom *et al.* 2017) conducted further research in the tropical forests of Kolasib district, Mizoram, Trishna Wildlife Sanctuary, Tripura and a sacred grove in Manipur, respectively. Chaudhury and Upadhaya (2016) estimated understory and detritus carbon storage at 50% of dry mass.	Brown and Lugo (1982), Brown *et al.* (1989), and Brown *et al.* (1993) made significant contributions to foundational studies on tropical forests across various geographic regions, consistently applying a standard carbon fraction of 50%. Ravindranath *et al.* (1997) estimated that carbon constitutes 50% of the living biomass across India's diverse forest ecosystems. Montagnini and Porras (1998) and Malhi and Grace (2000) reported similar values in their studies on humid tropical plantations and tropical forests, respectively. IPCC (2003) and FAO (2003) established a widely accepted default carbon fraction of 50%, representing the proportion of dry biomass composed of carbon. Ravindranath and Ostwald (2008) reaffirmed this standard through carbon pool assessments in countries such as Benin, Ghana, Morocco, Brazil, India, Vietnam, and Kazakhstan. Similarly, Dar and Sundarapandiyan (2015) estimated understory carbon storage as 50% of dry weight. Pearson *et al.* 2007) analyzed forest carbon sequestration and monitoring in the United States, reporting comparable values Li *et al.* (2015), in their study of Yunnan Province, Southwest China, found that broadleaf species conformed the 50% default carbon fraction, while coniferous tree components exhibited slightly lower values
C= 55% *B	Thokchom and Yadava (2017) studied forests in Manipur's Tamenglong, Chuurachandpur, Imphal East (Jiribam), Bishnupur and Thoubal districts. Bordoloi *et al.* (2019) examined pine and mixed forests in Arunachal Pradesh's Ziro Valley, Lower Subansiri district	Dicken (1997) studied forestry and agroforestry systems in Belize, Brazil, Guatemala, the Philippines, and the United States

in remote sensing and GIS-based techniques have enhanced large-scale biomass modelling. Future research should focus on integrating multiple methods to improve precision and applicability across diverse ecological landscapes.

Estimates of forest biomass and carbon across North East India

The variation in aboveground woody biomass, ranging from 15.70 to 1046.86 Mg ha⁻¹ (Fig. 3), underscores the substantial differences in carbon storage potential across diverse forest types in Northeast India. The highest biomass recorded in the Phayeng sacred forest of Manipur (Waikhom *et al.* 2017) highlights the effectiveness of traditional conservation practices in sustaining forest carbon stocks. Sacred groves, often safeguarded by customary laws, serve as biodiversity hotspots and contribute to long-term carbon sequestration. The minimal human interference in these forests facilitates the persistence of old-growth trees, which play a crucial role in maintaining ecosystem stability. Conversely, the lowest recorded aboveground biomass in *Dipterocarpus* forests of the same state (Thokchom and Yadava 2015) suggests that certain forest types may be more susceptible to biomass depletion due to ecological and anthropogenic pressures. Factors such as selective logging, deforestation, and land-use changes likely contribute to these lower biomass values. Understanding these drivers is critical for developing sustainable forest management strategies. Given the increasing pressures of climate change and deforestation, preserving high-carbon-stock forests, such as sacred groves, presents a viable strategy for carbon sequestration and biodiversity conservation in Northeast India.

Shrub and herbaceous biomass also exhibit significant variability across habitats due to ecological considerations. The reported biomass values for herbs and shrubs range from 0.013 to 4.09 Mg ha⁻¹ and 0.14 to 21.18 Mg ha⁻¹, respectively (Chaudhury & Upadhaya 2016, Das *et al.* 2021). These variations reflect differences in species composition, resource availability, and ecosystem function. While herbs contribute to nutrient cycling and minor carbon sequestration, shrubs make a more substantial contribution to carbon storage.

Belowground biomass (as depicted in Fig. 4) varies from 28.74 to 165.27 Mg ha⁻¹, illustrating differences in root biomass allocation across forest ecosystems. The relatively high belowground biomass values emphasize the role of root systems in carbon storage, particularly in intact forests. However, comprehensive assessments of root dynamics and their contributions to the overall carbon budget remain limited, especially in Northeast India.

A notable gap in research is the limited study of deadwood and litter biomass in the tropics, despite their significant role in carbon cycling. Deadwood biomass contributes to nutrient cycling, habitat provision, and long-term carbon storage. However, studies on deadwood remain scarce, and available data indicate high site-specific variations in coarse woody debris volumes. Deadwood biomass ranged from 0.11 to 18.76 Mg ha⁻¹ (Giri *et al.* 2019, Gogoi and Sahoo 2018), reflecting the variability in decomposition processes and forest stand characteristics. Litter biomass, ranging from 0.13 to 11.53 Mg ha⁻¹, is a critical component of forest carbon dynamics (Chaudhury & Upadhaya 2016, Giri *et al.* 2019), playing a key role in soil nutrient cycling, moisture retention and microbial activity, all of which influence ecosystem productivity. More research is needed to assess carbon turnover associated with deadwood and litter.

This integrated review, synthesizing data from various methodologies, provides a comprehensive assessment of biomass carbon across the eight Northeastern states of India. The mean total biomass carbon is estimated at 136.86 Mg ha⁻¹, with 100.76 Mg ha⁻¹ being attributed to aboveground biomass, 31.8 Mg ha⁻¹ to belowground biomass, 2.34 Mg ha⁻¹ to deadwood, and 1.96 Mg ha⁻¹ to litter (Fig. 5). These values are notably higher than those reported by the Forest Survey of India (FSI), likely due to the inclusion of a more extensive dataset with greater sampling coverage. This underscores the importance of comprehensive data integration for improving biomass carbon assessments.

CONCLUSION

Variability in biomass estimates may stem from differences in sampling techniques, forest types,

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disturbance regimes, and ecological conditions across the region. This review underscores the need for standardized methodologies and improved regional-scale assessments to enhance the accuracy of biomass carbon estimates. To further refine biomass estimates, future research should focus on harmonizing biomass estimation approaches and incorporating remote sensing and machine learning techniques to further enhance biomass carbon assessments in the region. Additionally, long-term monitoring of biomass components, particularly deadwood and litter, is essential for a deeper understanding of carbon fluxes in tropical forest ecosystems.

By advancing biomass estimation accuracy and supporting conservation efforts, this study contributes to the development of more effective carbon management strategies. Strengthening these initiatives will further reinforce the role of Northeastern India's forests in sustaining ecosystem balance and maximizing carbon storage potential.

ACKNOWLEDGMENT

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