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REVIEW

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A systematic review on the aboveground biomass and carbon stocks of Indian forest ecosystems

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Abstract

Background: Tropical forests play a crucial role as source and sink in global carbon cycle. Development and other anthropogenic activities have led to degradation of forest land, and ultimately, it results in loss of biodiversity and increases concentration of CO_2 in atmospheres. Therefore, there is urgent need to estimate regional and national level carbon stock for making forest-based policies and strategies for mitigation of CO_2. Patchy and sporadic information is available on biomass and carbon stock of Indian forests. The paper presents a systematic review and comprehensive account of studies conducted in different forest types in India.

Result: There are six major forest types found in India consisting of 15 groups and other subgroups with peculiar characteristics. Methodologies used by researchers for biomass/carbon stock estimation are destructive, nondestructive, tree inventories data, species-specific biomass estimation, and remote sensing. Majority of estimates are based on nondestructive allometric equation approach. Studies showed positive correlation between tree species, diameter at breast height, and biomass/carbon stock. Small- and medium-sized growing trees, invasive species, mixed forest, Agroforestry, and Agrosilviculture also play an important role in atmospheric carbon assimilation. The results of diverse forest carbon stock studies are broadly categorized in North, Central, and Southern India. Present review will be helpful for developing conservation policies and decision to increase carbon stock and also REDD+ program for particular forest ecosystem.

Conclusion: The systematic literature review was carried out to gather and summarize information from different studies conducted on forest ecosystems and quantification methods used for biomass estimation and carbon stock in different forests types and states of India. In general, great variability occurs in aboveground biomass and carbon stock on account of climatic and geographic differences. To obtain good and accurate estimations, following nondestructive approach, species-specific density-based equations are required from different habitats and also in relation to degradation status of forests. As such regional volume equations would increase error of estimations. The comprehensive account of data would be helpful to formulate strategies based on carbon sequestration in Indian forests for CO_2 mitigation.

Keywords: Tropical forests, Aboveground biomass, Carbon stock

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Background

Forest ecosystems act as source and sink of atmospheric carbon dioxide (CO_2) and are one of the most faithful options for carbon sequestration and play a crucial role in regulating global carbon cycle. Local, regional, and national carbon inventories of source and sinks of carbon are indispensable to assess the prospective role of various carbon sequestration pools for reducing atmospheric CO_2 accumulation, and therefore it is a pioneer step for preventing global warming. The studies also important for developing of systems/markets for national and international carbon credit/emission trading as well as in reducing emission from deforestation and forest degradation (REDD+) programs in developing countries (Han et al. 2007; NEFA 2002; Kale et al. 2004).

Article 2.1 of Kyoto Protocol addresses the issues related to global warming and asked to own responsibility to signatory countries to protect the sinks and reservoirs of greenhouse gases and increase afforestation, reforestation, and promote sustainable forest management (Yavaşli 2012). India is also one of the signatory in Kyoto Protocol; hence, various studies have been carried out at different parts of the country. However, the data is patchy and sporadic.

Precise assessment of CO_2 emissions as a result of land use changes, forest fire, degradation, and other anthropogenic activities are a few challenging issues for understanding global carbon cycle and hence for making policies. Therefore, recent researches mainly focus on biomass assessment to trim down uncertainties related to carbon cycle and emissions. Understanding of spatial distribution of biomass is a prerequisite to find out the sources and sinks of carbon (C) as a result of forest to degraded land and vice versa as well as their temporal variations (Yavaşli 2012).

Forests play a vital role in global carbon flux and act as carbon sink by storing large quantities of carbon for a long period of time. This storage of organic matter in biomass provides a lag for complete carbon emission on account of respiration. More than 40% of the global primary production in forest ecosystem is accomplished by tropical and subtropical forests (Beer et al. 2010). India is eighth among the top 10 most biodiverse countries (Butler 2016), with 21.05% (692,027 km^2) of its geographical area (3,287,263 km^2) under forest and tree cover (FSI 2011). Near about 173,000 villages are classified as forest fringe villages, and their dependency on forest resources is obviously large. Hence, it is very much important to assess the likely impact of forest degradation on projected climate change. In view of this, carbon/biomass stock studies play a crucial role in relation to develop and implement adaptation policies for both biodiversity conservation, protection, future sustainable utilization of forest resources, safeguarding the livelihoods of forest-dependent people, and reducing pressure on forest ecosystems (Kishwan et al. 2009).

According to fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007), limited information is available regarding the biomass, carbon stock/sequestration at national and regional level. This is particularly true for India as a few and sporadic forest biomass/carbon studies are available for carbon dioxide mitigation assessment (Ravindranath and Ostwald 2008). Another shortcoming is that, these estimates of carbon sequestration potential and stock are done without taking consideration of regional variations in species distribution, growth rates, and carbon sequestration rates. Nevertheless, such estimates are useful in formulating strategies for reducing CO_2 emissions with the help of REDD+ in global climate negotiations as a mitigation option (Gibbs et al. 2007; Murthy et al. 2012). Unrestricted utilization of forest resources, rapid population growth, and industrial development are manifested in land use changes, thereby reducing the extent and area of forests particularly in tropical countries like India.

A large number of vegetation/forest types occur in India due to immense climatic and edaphic variations. Therefore, all possible forest types ranging from alpine to very dry forests are occurring at different places. In view of the above variability, comprehensive data on biomass and carbon stocks are lacking at local, regional, and national level as required for millennium ecosystem assessment (MEA 2005) to workout strategies and policies for mitigating atmospheric CO_2 through organizing and conserving different forest vegetations.

The present review paper aims to evaluate forest ecosystems and forest types in relation to quantification methods and biomass estimates in India. Carbon stocks in different forest types are also evaluated based on studies available: information from various earlier studies with the help of systematic review papers, research papers, scientific reports, government policy reports available online or published literature for implementation of REDD+ policies.

Biomass and carbon studies in Indian forest ecosystem are quite challenging on account of varying localities and difficulties in accessibilities. No systematic data is available on studies on biomass/carbon of different regions and types of forests and uniform estimation methodology of Indian forests at one place. Although, a number of studies have been carried out on biomass/carbon stock estimations in India, they are sporadic and patchy in relation to particular forest ecosystem and methodology. The aim of the present paper is also to furnish comprehensive account of forest types, quantification methods used for biomass estimation, and biomass stock in different forest ecosystems in India.

Methods

In order to review and procure information from existing research on types of forest, basal area, biomass/carbon stock, sequestration pool in different forest ecosystems of India, a literature search was carried out during January 2017 to August 2017 using Web of Science (or Web of Knowledge), Google Scholar Citation, ResearchGate, offline journals, book chapters, Indian government scientific reports, Forest Survey of India data, Botanical Survey of India data, as well as reports published by Indian Ministry of Environment, Forest and Climate Change. The objective is limited to only Indian forest ecosystem in relation to biomass/carbon studies.

The methodology followed for search of literature consists of (a) generation of keywords as biomass/carbon stock, sequestration or pool estimation in different states in India, destructive methodology, nondestructive, allometric equations for biomass/carbon estimation in India for plantation forest, natural forest, Agroforestry, shrub biomass, types of forest, and their biomass status. (b) Search for literature on online using various sites (Google scholar citation, Web of science or knowledge, journal's sites), offline journals and book chapters from libraries of forest institutes of India, government policies and reports downloaded from websites. (c) Collection of main findings and highlighting them in review (d) interpretation of highlighted findings.

To collect more and more research articles for focusing biomass in Indian forest ecosystems, we also add or used positive, negative correlations between basal area and biomass, species diversity, species wise biomass/carbon estimation. The objective was to find most suitable or relevant published data for various Indian states and types of Indian forests. We also collected cross-references research articles which are relevant to our study. In all, 101 critical research articles were found meeting the aims and objective of study. Since the studies pertaining to the aims of the present paper are sporadic and not all the aspects are included in different papers available for Indian forest ecosystems, at places data are deficient and given as such. Main emphasis is given for biomass and carbon stocks in different forest types, e.g., tropical, temperate, alpine, and coniferous forests from Himalayan region.

It is worth to reveal that this study principally highlight the recent state of knowledge with the help of literature review instead of focusing on any data analysis or any statistical information. However, we used display data from all collected research articles whose references have been cited in the present paper.

Results and discussion

Types of forest in India

According to Champion and Seth (1968), there are six major forest types found in India which contain 15 groups and other subgroups with peculiar characteristic features, and all forests subgroups contained varying species composition (Table 1). This is the most exhaustive classification for forests in India that includes almost all climatic, edaphic, and successional vegetations.

Methods employed for estimation of aboveground biomass

In natural forest ecosystems, accumulated biomass is an important parameter for assessing sustainable utilization, productivity, and CO_2 sequestration from the atmosphere. Therefore, accuracy of estimation method is very important for a number of applications like global carbon cycle, timber extraction, to assess carbon stock tracking changes, etc. (Vashum and Jayakumar 2012). The aboveground forest biomass/carbon have been estimated by a number of methods and techniques based on inventory and stock tables. Most of the studies have been done in tropical forests with varying interests and objectives such as nutrient cycling, productivity, and sustainability of forest. The data is collected from limited to small, nonrandomly selected areas with insufficient focus on global carbon research (Brown et al. 1989). Most of the tropical tree inventories included large girth class trees with an interest in commercial timber. Further, the tropical forests are uneven aged and composed of all size and age classes. Omission of small or smaller girth class trees would many a times underestimate the important role of these individuals to the total forest biomass. Therefore, it is imperative to first analyze the structure and species composition of the vegetation and consider all or at least large proportion of the vegetation component for biomass estimation especially in tropical forests (Salunkhe et al. 2016).

There is no robust method developed for accurate biomass estimation. Existing methods are having controversies with variable accuracy ranges. Various methods are employed for measuring biomass/carbon include destructive (total harvesting of sample), nondestructive (measurable parameters like basal area, height, tree density), tree inventories data, species-specific biomass estimation, and remote sensing methods (Brown et al. 1989, 1999; Lu 2006; Murali et al. 2005). Absolute measurements of biomass can be taken up only at the time of felling which is not possible in all situations (Murali et al. 2005). Measurements for basal area, height, and species-specific gravity in field are good criteria for estimating biomass as nondestructive methods (de Gier 2003). In India, the selection system for felling is followed where only the marked trees are taken out leaving behind the immature/unmarked trees.

Field measurement method could be categorized into two type, viz., destructive and nondestructive biomass estimation methods. Destructive method is also popularly

Table 1 Major forests groups of Indian forest and their area

Major group	Group	Area (mha)	% Area
I. Moist tropical forest	1. Tropical wet-evergreen forest	4.5	5.8
	2. Tropical semi-evergreen forest	1.9	2.5
	3. Tropical moist deciduous forest	23.3	30.3
	4. Littoral and swamp forest	0.7	0.9
II. Dry tropical forest	5. Tropical dry deciduous forest	29.4	38.2
	6. Tropical thorn forest	5.2	6.7
	7. Tropical dry evergreen forest	0.1	0.1
III. Montane subtropical forest	8. Subtropical broad-leaved hill forest	0.3	0.4
	9. Subtropical pine forest	3.7	5.0
	10. Subtropical dry evergreen forest	0.2	0.2
IV. Montane temperate forest	11. Montane wet temperate forest	1.6	2.0
	12. Himalayan moist temperate forest	2.6	3.4
	13. Himalayan dry temperate forest	0.2	0.2
V. Subalpine forest	14. Subalpine forest	–	–
VI. Alpine Scrub	15. Moist – alpine scrub	3.3	4.3

Based on Champion and Seth (1968)

known as harvest method which is direct method for estimation aboveground biomass (AGB) and carbon stock (Gibbs et al. 2007). This method comprises of harvesting or felling of trees in a given area followed by weighing of different components harvested like trunk, leaves, branches, etc. (Nelson et al. 1999; Hashimotio et al. 2000; Lodhiyal and Lodhiyal 2003; Chung-Wang and Ceulemans 2004; Ravindranath and Ostwald 2008; Devi and Yadava 2009). This method is unwieldy and could only be applied to small area and not applicable to degraded forest and threatened forest species (Montès et al. 2000). Nevertheless, it is used to develop biomass estimation equations for assessing large-scale biomass (Navár 2009; Segura and Kanninen 2005).

Another method of field measurement is nondestructive approach. Taking measurable parameters, like girth at breast height (GBH), tree height, tree volume, and density of wood (Ravindranath and Ostwald 2008), and with the help of allometric equation (general or species specific), biomass is calculated (Brown et al. 1989; Nowak 1993; Hughes et al. 1999). With the help of forest inventories data, allometric equations are developed for assessing the biomass and carbon sequestration in forest ecosystem (Nelson et al. 1999; Chung-Wang and Ceulemans 2004; Montès et al. 2000; Navár 2009; Brown et al. 1989; Basuk et al. 2009). These equations are developed for single or mixture of species for comparisons of biomass estimations (Vashum and Jayakumar 2012).

Another method for biomass estimation is remote sensing and geographical information system (GIS). To estimate forest biomass, several studies have been conducted using remote sensing technology (Drake et al. 2003; Baccini et al. 2004; Anaya et al. 2009). However, for validation, data is required from field. The tree allometric equations appear more accurate in terms of selecting trees from the same species as well as growing in the same climate and soil environment in terms of their application (Clark and Clark 2000).

Indian forest ecosystem biomass/carbon estimates

The phytomass and carbon pool of Indian forest for the years 1880 to 1980 was calculated by Richards and Flint (1994) with the help of historical records, ecological data, and population-based forest biomass degradation model. Hingane (1991) used ecological studies–based mean phytomass density for estimation of carbon in two forest types. Using FAO inventories for ecological zone-wise five catogaries, Dadhwal et al. (1998) calculated phytomass carbon pool of 1980 and 1990 of Indian forests. Studies have been summarized in Table 2.

Manhas et al. (2006) reported the India's total carbon stock as 1085.06 and 1083.69 Mt in 1984 and 1994, respectively. The major forests contributed to carbon stock were of the order of: Miscellaneous forest > *Shorea robusta* forest > *Tectona grandis* forest > Temperate forest > Tropical forest > Bamboo forest, etc. Chhabra et al. (2002a, b) calculated total standing biomass (above and below ground) using biomass expansion factors. Their results showed that total biomass was 8683.7 Mt, that is, aboveground (6865.1 Mt) and belowground biomass (1818.7 Mt) contributed 79% and 21% to the total biomass, respectively, with mean biomass density of Indian forest as 135.6 t h^{-1}. From studies on carbon budget of the Indian forest ecosystems, Haripriya (2003) concluded

Table 2 Carbon pool estimates of Indian forest

Year	Forest area (M ha)	Methodology	Phytomass carbon pool (Tg C)	Source
1880/1980	102.7/64.6	Historical records, ecological data and population-based forest biomass degradation model	7940/3426	Richards and Flint (1994)
1980	52.6	Ecological studies-based mean phytomass density for two forest types	2587	Hingane (1991)
1980/1990	51.73	Using FAO inventories for ecological zone-wise five categories	3322/3117	Dadhwal et al. (1998)
1982/1991	64.2/64.01	State-wise RS-based forest area, field inventories based growing stock and crown density based BEFs for two classes	3978/4071	Dadhwal and Shah (1997)
1985	64.2	Growing stock volume data and single conversion factor	1994	Dadhwal and Nayak (1993)
1986	64.01	RS-based area, crown cover fraction for 16 forest types, Phytomass densities from ecological studies	4179	Ravindranath et al. (1997)
1993	64.01	State-wise growing stock FSI data, BEFs as function of GSVD for three crown density classes, four forest categories	4341.8	Chhabra et al. (2002a, b)
1995	63.96	Forest stratum-wise growing stock volume FSI data and a standard BEF relating to wood volume by IPCC	2026	Lal and Singh (2000)

Procured from: Chhabra et al. (2002b)
Mha 10^6 ha, *Tg C* 10^{12} gC, *BEF* biomass expansion factor, *FSI* forest survey of India, *GSVD* growing stock volume density, *IPCC* Intergovernmental Panel on Climate Change, *RS* remote sensing

that the Indian forest sector acted as a source of 12.8 Tg C for the year 1994. Estimated carbon pool size of trees and forests in India ranged from 41 to 48 Mg C ha^{-1} and from 39 to 47 Mg C ha^{-1} for 1992 and 2002, respectively (Kaul et al. 2011). Sheikh et al. (2011) estimated India's forest biomass and reported variations from 3325 to 3161 Mt for year 2003 to 2007, respectively. Net fluxes of CO_2 were 372 Mt and 288 Mt in I assessment and for II assessment period with annual emission of 186 and 114 Mt of CO_2, respectively.

For selected plantation forest of India, estimated rate of carbon flux was addressed by Raizada et al. (2003). Different species and their total carbon flux in planted area are summarized in Table 3. Important highlights of study are:

1. Short rotation planted forests having regular leaf shading patterns possess more capacity for carbon sequestration in litter.
2. Slow decomposing litter was produced by fast growing conifers leading to decline in ground flora as well as productivity with risk for fire damage.
3. As compared to mono culture, exotic and native species mixed plantation could be more efficient in carbon sequestration.
4. For wasteland afforestation and reforestation, fast growing hardy species like *Eucalyptus* would be ideal choice, and for the agrisilvicultural practices, soft woody species would be more ideal in plain areas.

Table 3 Estimated rate of carbon flux in selected planted forests in India

Tree species	Area (ha) (FSI 1999)	Av. litter production (t ha^{-1} yr.$^{-1}$)	C flux (Mt C yr.$^{-1}$)	Total C flux in the planted area (Mt. C yr.$^{-1}$)
Eucalyptus spp.	1360.91	4.50	2.03	27.5
Tectona grandis	1330.09	3.60	1.62	21.5
Acacia auriculiformis	564.67	3.03	1.36	7.7
Pinus roxburghii	381.54	4.94	2.22	7.1
Dalbergia sisoo	266.58	3.03	1.36	3.6
Shorea robusta	250.28	11.27	5.07	1.3
Gmelina arborea	148.01	2.17	0.97	1.4
Casuarina equisetifolia	134.00	3.15	1.41	1.9
Populus deltoids	47.48	3.71	1.66	0.8
Bombax ceiba	37.97	1.30	0.58	0.2

Raizada et al. (2003)

For rubber (*Hevea braziliensis*) plantation forest, Day (2005) estimated average carbon stock in North-Eastern states of India (Table 4). Results indicate that an average carbon store in rubber plantation is around 136 t c ha^{-1} out of which 92.7 t c ha^{-1} is contributed by soil and addition 2.40 t c ha^{-1} through litter fall and undergrowth vegetation. Also about 7 Mt carbon remain stored in rubber plantation (area 51,510 ha in 2002–2003).

For the tropical dry forest ecosystem of India, the allocation of plant biomass (t ha^{-1}) in different components is given in Table 5.

A comprehensive account of standing biomass for different forest types of India was given by Ravindranath et al. (1997) (Table 6).

Other sporadic studies of biomass/carbon estimation from different parts of India

These studies are broadly categorized under North, Central, and Southern forest ecosystem of India.

North Indian forest ecosystem biomass/carbon estimation

Forest of Himachal Pradesh in Himalayan range had 1158 t ha^{-1} as mean AGB (Sharma et al. 2008). Devi and Yadava (2009) carried out study for estimation of AGB and net primary productivity of semi-evergreen tropical forest of Manipur, North Eastern India, following harvest method. A positive correlation between tree species, DBH, and AGB of trees was also reported. In Garhwal Himalaya of Uttrakhand, the total live tree biomass density ranged from 215.5 to 486.2 Mg ha^{-1} and live C density varied from 107.8 to 234.1 Mg C ha^{-1} (Gairola et al. 2011). The total biomass carbon pool production of an old growth *Pinus kesiya* Royle *ex* Gordon forest in North Eastern India was 460.5 Mg ha^{-1} of which 91.20% was AGB and 8.8% below ground biomass. Out of total biomass, 77% contribution was that of *P. kesiya*, 13.5% of broad-leaved tree species, 0.12% of shrub, 0.03% of herb, and 0.5% of litter (Baishya and Barik 2011).

According to Sharma et al. (2011), carbon stock on different slope aspects in seven major forest types of temperate region of Garhwal Himalaya ranged from 77.3 C Mg ha^{-1} on South-East aspect to 291.6 C Mg ha^{-1} on North-East aspect with total carbon density of 118.1 C Mg ha^{-1} and 469.1 C Mg ha^{-1}. At high-altitude forests of central Himalayan region, Verma et al. (2012) assessed the carbon storage capacity of *Quercus semecarpifolia*. These forests had carbon ranging between 210.26 and 258.02 t ha^{-1} in their biomass in 2009 and mean carbon sequestration rate between 3.7 and 4.8 t ha^{-1} yr.$^{-1}$, respectively.

In sacred forest of Tehri of Garhwal Himalaya, Uttarakhand, biomass and total carbon density of different species based on nondestructive method were 1549.704 Mg ha^{-1} and 774.77 Mg ha^{-1}, respectively. Maximum biomass and carbon density was recorded in *Pinus wallichiana* (Pala et al. 2013). According to Borah et al. (2013) in the Cachar district of Assam, Northeast India, aboveground biomass ranged from 32.47 Mg ha^{-1} to 261.64 Mg ha^{-1} and carbon stock ranged from 16.24 Mg ha^{-1} to 130.82 Mg ha^{-1}, respectively. Interestingly, small to medium trees contributed more aboveground biomass and carbon stock as compared to large trees. Nautiyal and Singh (2013) estimated carbon stock potential of Oak and Pine forests in Garhwal region of Central Himalayas. Total carbon density estimates were 2420.54 Mg ha^{-1} for Oak and 986.93 Mg ha^{-1} for Pine forests.

Giri et al. (2014) made assessment of biomass and carbon stock in *Tectona grandis* plantation in Dehradun forest division. The whole ecosystem biomass was 218.22 t ha^{-1} of which Tectona *grandis* contributed 147.50 t ha^{-1}, five associated species as 65.62 t ha^{1}, and shrub and herb species as 2.218 and 0.773 t ha^{-1}. At Srinagar hydroelectric project, Uttarakhand, the total tree carbon density ranged in between 273.39 t ha^{-1} and 94.38 t ha^{-1}. Arora et al. (2014) estimated AGB and C stock in an age series of *Populus deltoides* plantation at Tarai region of central

Table 4 Carbon sequestration (t ha^{-1}) by planted forest of rubber in North Eastern India

State	Rubber planted forest area in 2002–2003 (ha)	Carbon store rubber		Annual C addition from under growth	Total carbon
		Plant	Soil		
Tripura	28,853	1762.9	1915.8	69.2	3747.9
Assam	13,208	807.0	919.2	31.7	1757.9
Meghalaya	4586	280.2	451.2	11.0	742.4
Nagaland	2087	127.5	225.4	5.0	357.9
Manipur	1708	104.3	102.4	4.1	210.8
Mizoram	696	42.5	62.4	1.7	106.6
Arunachal Pradesh	372	22.7	58.4	8.9	90.0
Entire North East	51,510	3147.1	3734.8	131.6	7013.5

Day (2005)

Table 5 Allocation of plant biomass (t ha^{-1}) in different components of tropical dry forest of India

Locality	Plant biomass			Source
	AG	BG	Total	
Varanasi	–	7.6	–	Bandhu (1970)
Varanasi	205.5	34.3	239.8	Singh (1975)
Udaipur	28.2	–	–	Ranawat and Vyas (1975)
Dehra Dun	129.6	–	–	Kaul et al. (1979)
Varanasi	64.3	9.5	78.3	Singh and Singh (1981)
Chandraprabha	95.0	–	–	Singh (1989)
Tripura	114	24.40	138.6	Negi et al. (1990)
Coimbatore	27.6	11.1	38.6	George et al. (1990)
Haldwani	74.6–164.0	15.4–17.9	90.0–181.9	Negi et al. (1995)
Chhindwara	28.1–85.3	9.1–15.6	37.1–100.9	Pande (2005)
Madhya Pradesh (Dry Deciduous)	54.9	–	–	Salunkhe et al. (2016)
Madhya Pradesh (Mixed Deciduous)	44.5	–	–	Salunkhe et al. (2016)

Himalaya region of India, showing an increase from 0.5 Mg ha^{-1} at 1 year to 90.1 mg ha^{-1} at 11 years. The total carbon stock (AGB and soil) increased from 64.4 mg ha^{-1} at 1 year to 173.9 mg ha^{-1} at 11 years. They concluded that *Populus deltoides* as a viable option for sustainable production and carbon mitigation. In the agroforestry land use system of Kwalkhad water-shed of middle Himalayan region of Himachal Pradesh, India, Goswami et al. (2014) evaluated carbon sequestration and C credits as 14.78 mg ha^{-1} in agrisilvihorticulture and 14.45 Mg ha^{1} in agrihortisilviculture systems.

Kumar and Sharma (2015) estimated forest carbon (C) stock of Balganga Reserved Forest (BRF) in district Tehri Garhwal, Uttarakhand, India. Results showed highest total biomass density (TBD) and total carbon density (TCD) estimates at site III in the altitudinal range of 1800–2600 m as 108.26 and 53.45 Mg ha^{-1} followed by site II in the range of 1600–1800 m as 83.92 and 41.96 Mg ha^{-1}, and lowest at site I in the altitudinal

Table 6 Standing biomass of different forest types of India

Sr. No.	Forest Types	Standing biomass (t ha^{-1})	Reference
1	Tropical wet evergreen	607.7	Rai (1981)
2	Tropical semi evergreen	468.0	Swami (1989)
3	Tropical moist deciduous	409.3	Swami (1989)
4	Littoral and swamp	213.8	Singh (1989)
5	Tropical dry deciduous	93.8	Singh (1990)
6	Tropical thorn[a]	40.0	
7	Tropical dry evergreen[b]	40.0	
8	Subtropical broad leafed hill	108.7	Toky and Ramakrishnan (1982)
9	Subtropical Pine	210.8	Chaturvedi and Singh (1984)
10	Subtropical dry evergreen[c]	159.7	
11	Montane wet temperate	237.67	Yadava (1986)
12	Himalayan moist temperate	562.2	Rana (1985)
13	Himalayan dry temperate[d]	169.1	
14–16	Subalpine and alpine	127.4	Yoda (1968), cited by Cannell (1982)

Source: Ravindranath et al. (1997)

[a]Tropical thorn forest were assumed to have 40% of the crown cover of tropical dry deciduous forests as they appear alongside the tropical dry deciduous forest; 40% of standing biomass of deciduous forests were assumed to be the standing biomass of tropical thorn forests, which is 37.52 t ha^{-1} further rounded off to 40 t ha^{-1}

[b]Same as tropical thorn forest

[c]Since it occurs between subtropical pine and tropical dry deciduous forests, a mid value between the standing biomass values of these two forests types is used

[d]Since it occurs between subtropical pine and subalpine forests, a mid value between the standing biomass values of these two forests types is used

range of 1000–1400 m as 57.22 and 28.61 Mg ha^{-1} with an average of 83.13 and 41.56 Mg ha^{-1}, respectively. According to Mandal and Joshi (2015), invasive shrubs also play an important role in atmospheric carbon assimilation. They calculated highest biomass (13,559.60 kg ha^{-1}) and carbon density (6373.01 kg ha^{-1}) of *Lantana camara* L. with the help of allometric equation at Doon valley, Western Himalaya. In the Cypress forest of central Himalaya, Rana et al. (2015) reported that total biomass of trees across all the sites ranged between 178 and 431 t ha^{-1}, while carbon stock ranged between 89.07 and 206 t ha^{-1}.

Singh et al. (2016) estimated carbon sequestration potential of tropical dry deciduous forests in three protected forests of Gurgaon district, southern Haryana. They found the AGB of trees in the three forests as 37.93 to 63.73 Mg ha^{-1} and below ground biomass as 11.12 to 17.81 Mg ha^{-1}. The total carbon pools in the three forests were 52.59 Mg ha^{-1} at *Ailanthus excelsa*–*Cassia fistula* forest, followed by 34.17 Mg ha^{-1} for *Acacia leucophloea*–*Balanites aegyptica* forest, and 33.61 Mg ha^{-1} in *Anogeissus pendula*–*Acacia leucophloea* dominated forest. Majumdar et al. (2016) estimated biomass of selected tropical forest patches of Tripura, Northeast India, using allometric equations. The biomass ranged in between 37.85 to 85.58 Mg ha^{-1}. Studies from community-managed forest at Garhwal Himalaya, India, showed total biomass and carbon density as 132.74 Mg ha^{-1} and 66.36 Mg ha^{-1}, respectively (Mahato et al. 2016). Very high aboveground biomass density (78.20 ± 17.41 t ha^{-1}) was found in *Quercus leucotrichophora* followed by *Pinus roxburghii*. In tea agroforestry system of Barak valley, Assam, North East India, Kalita et al. (2016) estimated carbon stock using species specific volume equations, wood-specific gravity, and biomass expansion factor. The results showed that carbon stock in 6, 14, and 22 years old plantation were 44.8 ± 1.3, 50.2 ± 4.6, and 56.7 ± 4.9 Mg C ha^{-1}, respectively.

Thokchom and Yadava (2017) estimated biomass and carbon stock along an altitudinal gradient in the forest of Manipur, Northeast India. The aboveground biomass ranged between 124.56 and 254.99 t ha^{-1} and carbon stock ranged from 60.09 to 121.43 t ha^{-1} across the study area. At Poplar (*Populus deltoides*) agroforestry system in Yamunanagar and Saharanpur districts of Northwestern India, biomass production and carbon stock were estimated by Rizvi et al. (2011). The contribution of Poplar plantation to carbon storage was found 27–32 t ha^{-1} in boundary system, whereas it was 66–83 t ha^{-1} in agrisilviculture system at rotation period of 7 years in the two districts. They also concluded that Poplar plantations may play a significant role in atmospheric CO_2 assimilation. In the Eastern Himalayas, North-East India, Gogoi et al. (2017) estimated carbon stock of rain forest using suitable regression equations, and they found highest stock (306.61 ± 17.14 Mg C ha^{-1}) in least disturbed site. Moderately distributed and highly distributed site showed 169.91 ± 2.59 Mg C ha^{-1} and 102.43 ± 3.18 Mg C ha^{-1}, respectively. They also attributed that carbon sequestration is impacted by anthropogenic disturbances in forest ecosystems. Niirou and Gupta (2017) reported tree carbon stock ranging from 25.59 t ha^{-1} to 164.81 t ha^{-1} and basal area from 10.13 m^2 ha^{-1} to 92.04 m^2 ha^{-1}, in Oak- and Pine-dominant forests using regression equation models at Senapati district of Manipur, India.

Central Indian forest ecosystem biomass/carbon estimation

Kale et al. (2004) developed allometric equations for estimation of bole biomass of five prominent species from dry deciduous forest in Shivpuri district, Madhya Pradesh, Central India, using nondestructive method. For estimation of AGB, Bijalwan et al. (2010b) used non-destructive approach based on DBH, height, and volume equations. They reported 78,170.72 Mg, 81,656.91 Mg, and 7470.45 Mg C in mixed, degraded, and Sal mixed forests, respectively, in dry tropical forests of entire area of Chhattisgarh region of Central India using satellite remote sensing and GIS. Bijalwan et al. (2010a) estimated biomass and carbon in dry tropical forest of Chhattisgarh region in India with the help of satellite remote sensing and GIS technology. The results of standing volume, AGB, and C storage varied from 35.59 to 64.31 m^2 ha^{-1}, 45.94 to 78.31 Mg ha^{-1}, and 22.97 to 33.27 Mg ha^{-1}, respectively. With the help of DLR-ESAR multi-frequency data, Nizalapur et al. (2010) estimated the AGB of Indian tropical forests in Gujarat, India. They reported that C-band ESAR data predict 70 Mg ha^{-1}, L-band up to 150 Mg ha^{-1}, and P-band up to 200 Mg ha^{-1}. Phytomass of moist deciduous forest of Gujarat, India, estimated with the help of spectral modeling showed a range from 6.13 t ha^{-1} to 389.166 t ha^{-1}, while it was 5.534–134.082 t ha^{-1} using area weights for 250 × 250 m sites. The mean biomass of study area was reported as 40.50 t ha^{-1} with mean C density of 19.44 t C ha^{-1} (Patil et al. 2012). Chaturvedi et al. (2012) addressed the effects of grazing, harvesting, and carbon accumulation of juvenile trees at five sites of tropical dry forest of Uttar Pradesh, India. The results indicate that the carbon density in the juvenile tree population ranged from 271 to 966 kg-C ha^{-1} and carbon accumulation from 10 to 2010 g-C cm^{-2} yr.$^{-1}$.

Kumar et al. (2011) estimated mean AGB from northern Haryana, the range being from 30.46 Mg ha^{-1} to 310.10 Mg ha^{-1} across all forest types. While the total AGB and C stocks were 26.99 Tg and 12.96 Tg. According to Kumar et al. (2011), the biomass of trees varies with age from 183.7 ± 3.21 to 298.3 ± 3.57 t ha^{-1} in *Butea monosperma* forest ecosystem in Western India, Rajasthan. Pandya et al. (2013) estimated carbon storage in 25 species from Gujarat state of India, using nondestructive allometric equation approach. They reported that trees store 177.5 million tonnes of carbon out of which the selected 25 tree species contributed (the sum of all species carbon) 421.47×10^{-6} million tones carbon. The lowest carbon storage value estimated in *Emblica officinalis* 1.77tC and maximum carbon storage found in *Tamarindus indica* 55.95tC. Studies on fast-growing tree plantation under agroforestry system adopting strategies for sustainable tree-crop production and C sequestration improvement in subhumidtropics of Chhattisgarh, India, were done by Swami and Mishra (2014). They reported that total biomass varied from 12.9 Mg ha^{-1} to 25.1 Mg ha^{-1} in 5-year-old *Ceiba pentandra* trees, in *Gmelina arborea* 9.9 Mg ha^{-1} to 21.4 Mg ha^{-1}, and in *Populus deltoides* clones, total biomass ranged from 48.5 Mg ha^{-1} to 62.2 Mg ha^{-1}.

Salunkhe et al. (2014) estimated AGB and C stock in tropical deciduous forests of state of Madhya Pradesh, India. The AGB ranged from 3.99 to 53.90 t ha^{-1} and carbon stock ranged from 1.89 to 25.6 t ha^{-1} across different study sites. According to Chaturvedi and Raghubanshi (2015), the average aboveground carbon density and carbon accumulation of mono and multispecific *Tectona grandis* and *Shorea raobusta* forests in tropical dry region of India were 136 t cha^{-1} and 5.3 t cha^{-1} yr.$^{-1}$, respectively. Lal et al. (2016) estimated carbon storage pattern in natural and plantation forests of subhumid tropics in Barnawapara Wildlife Sanctuary, Chhatisgarh, India, using allometric equations. The maximum total (above and below) carbon was found in closed natural forest (208.22 Mg ha^{-1}) followed by open natural forests (95.11 Mg ha^{-1}) and Teak plantation (56.06 mg ha^{-1}). They also concluded that in terms of carbon storage, natural forest has an edge over the plantation forest. In studies on tropical deciduous forest ecosystems of Madhya Pradesh, India, Salunkhe and Khare (2016) estimated carbon stock in four different types of forests, viz., mixed non-Teak forest (MNTF) as 25–54 Mg ha^{-1}, dry mixed non-Teak forest (DMNTF) as 13–42 Mg ha^{-1}, Teak-dominated forest (TDF) as 33–53 Mg ha^{-1}, and dry Teak forest (DTF) as 16–24 Mg ha^{-1}. Biomass and carbon stocks of different tree plantations of eastern Chhatisgarh, India, were highest (942.50 t ha^{-1}) in *Albizia lebbeck* followed by *Eucalyptus globules* (520.62 t ha^{-1}), *Terminalia arjuna* (143.12 t ha^{-1}), and *Azadirachta indica* (106.87 t ha^{-1}) (Bhardwaj and Chandra 2016).

South Indian forest ecosystem biomass/carbon estimation

Mani and Parthasarathy (2007) estimated AGB in inland and costal tropical dry evergreen forests of Peninsular India. Using basal area method, they reported that AGB ranged from 39.69 to 170.02 Mg ha^{-1}, whereas estimates based on basal area and height method, it was 73.06–173.10 Mg ha^{-1}. In both the forests types, basal area (BA) and AGB showed positive relationship. Kale et al. (2009) estimated carbon sequestration and concluded that natural plantation had highest rate (20.27 t ha^{-1}) of carbon sequestration than mixed moist deciduous natural forest in Western Ghats. Bhat and Ravindranath (2011) work out incremental aboveground standing biomass in tropical rain forest of Uttara kannada district of Western Ghat using specific equation approach, which ranged from 6.40 to 144.67 t ha^{-1}. The biomass productivity and carbon stocks of farm forestry and agroforesty systems of *Leucaena* and *Eucalyptus* in Andhra Pradesh were analyzed by Prasad et al. (2012). The carbon stocks of *Leucaena* and *Eucalyptus* are 62 Mg ha^{-1} and 34 Mg ha^{-1}, respectively. They also concluded that *Leucaena* and *Eucalyptus* system can play an important role as carbon sinks.

Sundarapandian et al. (2013) estimated biomass in five study sites—four plantations and a natural forest at Puthupet, Tamil Nadu. The AGB for *Anacardium occidentale*, *Casuarina equisetifolia*, *Mangifera indica*, *Coccus nucifera*, and natural forest were 32.7, 38.1, 121.1, 143.2, and 227.2 Mg ha^{-1}, respectively. Maximum carbon stock was reported from natural forest site (131.8 Mg ha^{-1}). Study suggested that for reducing atmospheric CO_2 concentration, managed plantations are helpful. The aboveground biomass and carbon stock of Mysore district (19 and 9 t ha^{-1}, respectively) and Hassan district (24 and 12 t ha^{-1}, respectively) were reported by Devagiri et al. (2013) for dry deciduous forest of western part of Karnataka, India, using allometric volume equations.

Pragasan (2014) determined AGB of tree species in the Pachaimalai forest of the Eastern Ghats in India. Results showed that the average biomass value was 25.3 ± 5.6 t ha^{-1} with a range from 4.2 to 103.5 t ha^{-1} with the total stock 12 ha as 608.5 t. According to Sundarapandian et al. (2014), total carbon stock of Pondicherry University campus forest was 14.9 Mg ha^{-1}. Rao and Rao (2015) studied the total standing biomass and carbon stocks of tropical deciduous forest of Nallamalais, India. Results revealed that biomass and carbon stock of study area were 56.47 Mt. and 26.34 Mt., respectively. In tropical forests of Bodamalai hills, Tamil Nadu, Pragasan (2015) recorded total carbon stock as 10.9 ± 3.6 tC ha^{-1} with tree carbon stock from 3.53 tC ha^{-1} to 38.92 tC ha^{-1}. Vivek and Parthasarathy (2015) reported trees and lianas carbon stock from tropical dry evergreen forests of Coromandel Coast of India. The total trees AGB were 3025.8 Mg ha^{-1} across ten sites. The AGB of lianas ranged from 2.24 Mg ha^{-1} to 42.13 Mg ha^{-1} with total contribution of 153.76 Mg ha^{-1}. Subashree and

Sundrapandian (2017) carried out carbon inventories for savannah ecosystems of Kanyakumari Wildlife Sanctuary, Western Ghats, India. Results showed that the total vegetation carbon accounted was 216.2 Mg C ha^{-1} and 206.6 Mg C ha^{-1} at two different sites.

Conclusion

Forests are the principal natural carbon pool and act as carbon source and sink. Tropical forests are potentially capable to mitigate climate change and global warming by sequestering carbon from atmosphere. Understanding of global carbon cycle is a difficult and complex task due to changing land use, degradation of existing forests, and other anthropogenic influences. Further, accurate data on carbon sequestration and stocks are highly deficient especially from tropical forests of India where diverse forest communities exist due to highly variable climatic and geographical conditions.

In the present paper, we tried to explore and comprehend scientific studies conducted in Indian forests related to aboveground biomass and carbon stock from almost all forest types including plantations and agroforestry systems. The methods involved for estimation of biomass and carbon stock are classified as destructive and nondestructive approaches. While the former is now not practically considered due to conservational point of view except in small uniform forest communities, the latter depends on measurable parameters such as girth at breast height, tree height, volume, and wood density. Estimation are also carried out based on remote sensing data; however, it also requires validation from field.

Tropical wet evergreen forest types appear to stock more biomass. However, tropical deciduous forests contribute more to the total biomass and carbon stock on account of their area. Studies indicate that for estimation, usually general volume equations are used that have been developed by forest institutes and other workers. Species-specific equations are also available; however, they may not give sufficiently good estimation due to forest degradation variations and habitat variability. Therefore, there is a need to develop specific equations from different habitats and conditions of degradation in forests.

Present paper summarized various estimates from different forest types in India, related to biomass and carbon stock, pool, and sequestration. The estimates can be utilized for generating a data base that could be useful for policy-making particularly related to mitigation of climate change and conservation.

Abbreviations

AGB: Aboveground biomass; BA: Basal area; C: Carbon; REDD+: Reducing emission from deforestation and forest degradation

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