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Wood Specific Gravity in Indian Forests: A Review

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ABSTRACT

Wood specific gravity (WSG) is an important attribute for biomass estimation of forest trees. It is an important factor in converting forest volume into biomass. However, a number of factors like climatic condition, geographic location, management practice, age of tree, location of sample collection etc. may affect WSG. In India, forests have been classified into 6 major groups, 16 groups and other sub groups on the basis of climatic, edaphic and successional variations. A number of studies conducted on above ground biomass and carbon stock using non-destructive method used global, regional or reported WSG leading to inaccuracies in biomass estimation. The present paper is a comprehensive review on methodology of wood specific gravity estimation, wood specific gravity values of a number of species reported from different forest groups of India. A total of 88 critical research papers and reports for last 20 years were found meeting the aims, were collected from relevant sources. Methodology for determining WSG is discussed for accurate estimation. Comparative analysis of common species distributed in different forest groups does not show a generalized trend for WSG, as the same forest group does not exhibit similar WSG in tree species. However, it is evident that juvenility effect has greater bearing on wood specific gravity variation than climate. Analysis of data shows a greater bearing of edaphic factor on WSG, than the climatic factor. It is suggested that for estimation of biomass, habitat specific WSG is ideal to attain accuracy.

Key words: Above ground biomass, forest groups, wood specific gravity, carbon stock, wood core, wood density, functional trait, non-destructive method.

INTRODUCTION

To generate carbon credits under the Reducing Emission from deforestation and forest Degradation program (REDD+), accurate estimates of forest carbon stocks are required (Ramananantoandro et al. 2015). Above ground biomass (AGB) is an essential aspect of studies of carbon stocks and to study the effects of deforestation and carbon sequestration in relation to global carbon balance (Ketterings et al. 2001). It is also useful for comparing structural and functional attributes of forest ecosystems across a wide range of environmental conditions (Brown et al. 1999). Tropical forest ecosystems play important role in global carbon balance by storing approximately half of the world's living terrestrial biomass (Salunkhe et al. 2014). Carbon estimation by non-destructive method is one of the well founded practices in place of destructive method. A number of studies conducted for estimation of AGB by non-destructive method mostly used measurable tree parameters like diameter, height and wood specific gravity (WSG) along with allometric equation (general and species specific) (Brown and Lugo 1984, Chave et al. 2001, Clark et al. 2001, Cummings et al. 2002, Baker et al. 2004, Malhi et al. 2004, Nascimento and Laurance 2004, Segura and Kanninen 2005, Salunkhe et al. 2014, 2016, Raha et al. 2020).

Although the choice of allometric model remains the most common source of error in biomass estimation (Chave et al. 2005, 2014), possible errors in the choice of wood specific gravity (WSG) measurements should not be ignored, as it is the second best predictor of a tree's biomass (Chave et al. 2004, 2005, Molto et al. 2013, Chave et al. 2014). WSG is defined as the density of oven dry wood relative to the density of water whereas wood density is the weight per volume, which includes the weight of water contained by the wood (Gao et al. 2017). Plant functional traits are the important determinants of survival and fitness and wood density is one of the key traits which is linked to mechanical stability, growth rates and drought and shade-tolerance strategies (Ogle et al. 2014). WSG has become a common subject in recent years as plant biologists look for broad-spectrum functional traits and assess their ecological and evolutionary significance (Muller-Landau 2004, Chave et al. 2006, King et al. 2006, Van Gelder et al. 2006, Swenson and Enquist 2007).

Wood density is a crucial feature associated with many aspects of a plant's ecology since it reflects a plant's carbon expenditure in its water conducting tissues relative to the size of the stem (Chave et al. 2009), including life history strategy, functional physiology, mechanical properties and architecture (Poorter et al. 2003, Santiago et al. 2004, King et al. 2006, Van Gelder et al. 2006). Although growth rate is negatively correlated with wood density (Enquist et al. 1999, Roderick 2000, Muller-Landau 2004, King et al. 2005), but the survival and life span of trees are positively correlated (Muller-Landau 2004).

WSG is an important factor in converting forest volume data into biomass (Fearnside 1997). It is a direct reflection of the amount of carbon present in the forest as biomass (Woodcock and Shier 2003) and it is strongly correlated with carbon density per unit volume, making it useful in estimating ecosystem carbon storage and fluxes (Fearnside 1997, Mani and Parthasarathy 2007). However, a number of factors like climatic condition, location and management practices may cause the WSG variation (Ketterings et al. 2001). Further, the location of the wood sample within a tree, the geographic range of the tree species and site conditions of trees can also cause variation in wood specific gravity (Keduolhouvonuo and Kumar 2017).

Many studies have shown high intra-community variance in wood density (Borchert 1994, Woodcock 2000, ter Steege and Hammond 2001) as a result of niche partitioning (Borchert 1994) and strategies adopted in life cycle (Muller-Landau 2004). Significant variations in WSG have been linked to precipitation, temperature (Wiemann and Williamson 2002, Mani and Parthasarathy 2007, Swenson and Enquist 2007) and altitude gradients (Chave et al. 2006, Swenson and Enquist 2007) at diverse macro-environmental scales.

A large number of forest types occur in India due to climatic and edaphic variations. Therefore, almost all possible forest communities ranging from alpine to very dry forests find places in India. Accurate assessment of terrestrial standing biomass of trees largely depends upon the accuracy of WSG of forest trees. A number of researchers have estimated above ground biomass without considering the regional and site specific variations of the WSG (Ahmedin et al. 2013, Salunkhe et al. 2014, 2016, Raha et al. 2020). So far, only few attempts have been made to assess WSG of different forest tree species in different forest types in India (Mani and Parthasarathy 2007, Sheikh et al. 2011, Chaturvedi and Raghubanshi 2013). Therefore, the data available on carbon flux at national level is liable to be inaccurate. The present paper aims to provide a comprehensive account of WSG of some tree species documented from different forest groups of India, and methods used for estimating wood specific gravity of forest trees. The data for WSG for tree species for tree species from different forests and environment will be increase the accuracy of biomass estimates in India.

METHODS

In order to review and acquire information from existing research on forest type and their WSG, a literature search was carried out for the work reported in past two decades during January 2020 to February 2020 using Web of Science, Google scholar citation, Research Gate, offline journals, book chapters, and Government of India scientific reports.

The methodology followed for search of literature consists of (a) generation of keywords such as wood specific gravity, above ground biomass, types of forest, wood characteristics of tree species, physical properties of wood, allometric model etc. (b) search for literature on online using various sites (Google scholar citation, Web of science, journal's site), offline journals and book chapters from libraries (c) collection of main findings and highlighting them in review (d) interpretation of highlighted findings.

Further to collect more research articles focusing WSG in different Indian forest ecosystems; we also used positive and negative correlation between location and WSG, species diversity and species wise WSG estimation. The objective was to find most suitable or relevant published data for various locations in different states and different forest groups of India. We have also collected cross-referenced research articles which are relevant to study. Total 88 critical research articles were found meeting the aims and objectives of study. Since 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 types, at places data are deficient and given as such.

Main emphasis is given for WSG in different forest groups, e.g., moist tropical, dry tropical, montane subtropical and montane temperate forests. It is worth mentioning that this review principally highlights the recent state of knowledge with the help of literature review instead of focusing on any data analysis or any statistical information.

RESULTS

Forest groups in India

According to Champion and Seth (1968), there are six major forest groups found in India which contain 16 groups (Fig. 1) and other sub-groups with characteristic features, and all forests subgroups contain varying species composition. Table 1 incorporates major groups and groups of forests in India, along with respective forest cover, abundant species and number of species reported in each group. This is the most exhaustive classification for forests in India that includes almost all climatic, edaphic and successional vegetations. Forest communities of India are highly diversified and inhabit a variety of plants. The total forest cover of the country (Fig 2), as per current assessment is 7,12,249 sq km which is 21.67% of the total geographic area of the country. In terms of canopy density classes, area covered by very dense forest is 99,278 sq km (3.02%), moderately dense forest is 3,08,472 sq km (9.39%) and open forest is 3,04,499 sq km (9.26%). Very dense and moderately dense forests constitute over 57% of the total forest cover of the country (FSI 2019).

Methods adopted for determining wood specific gravity in India

In natural forest ecosystems, the estimation of accumulated biomass is an important parameter for assessing carbon flux, carbon sequestration potential of the forests and sustainable utilization. Generalized WSGs, either national or regional have been used for volume equations, leading to inaccuracies. Ramananantoandro et al (2015) had reported variation of 5 Mg/ha carbon when they have used habitat specific WSG data in place of data available in the international literature. Therefore, accuracy in estimation method of biomass and carbon stock largely depends upon the WSG of trees and habitat characteristics.

In India, mainly two methods have been followed for estimating WSG. They are - Maximum moisture content method (Smith 1954) and method provided by forest products laboratory (USDA 1952).

a) Method by forest product laboratory (USDA 1952)

$$\text{Specific gravity} = \frac{D}{V},$$

where D is the weight of dried sample in g; and V is the volume of fresh sample in cubic centimeters. Volume can be calculated by Water displacement method which follows Pythagorean Theorem or mathematically volume is calculated by dimensional method i.e.

$$V = \frac{\pi}{4} D^2 L$$

where, D is the mean diameter of wood sample and L= total length of sample. Dry weight can be obtained by the same sample by drying it in oven at 103±2°C until constant weight is obtained.

b) Maximum moisture content method by Smith (1954)

This is a simple technique to obtain specific gravity on the basis of green volume by only determining the weight of water saturated samples and the weight of oven dried samples. Dry weight can be obtained by the same sample by drying it in oven at 103±2°C until constant weight is obtained.

$$G_f = \frac{1}{\frac{M_m - M_o}{M_o} + \frac{1}{G_{so}}}$$

Where G_f is the WSG based on gross volume, M_m is the weight of water saturated samples

Table 1. Major forest groups of Indian forest based on Champion and Seth (1968), their group wise percentage forest area cover, abundant forest species in tropical moist deciduous forest and tropical dry deciduous forest and number of species identified in each forest group (NFSO - Natural forest of seed origin; NFCO - Natural forest of coppice origin and MMF - Man made forest

Major groups	Groups	Forest cover area in %*			Abundant forest species*	No. of species identified*
		NFSO	NFCO	MMF		
I. Moist tropical forest	1. Tropical wet-evergreen forest	86.14	5.43	8.43	*Olea dioica*, *Schleichera trijuga*, *Knema attenuata*, *Hopea* species and *Syzygium cumini*	448
	2. Tropical semi-evergreen forest	75.49	17.02	7.49	*Terminalia paniculata*, *Castanopsis* species, *Terminalia crenulata*, *Tectona grandis* and *Schima wallichii*	485
	3. Tropical moist deciduous forest	78.14	13.91	7.95	*Shorea robusta*,*Tectona grandis*,*Terminalia crenulata*, *Anogeissus latifolia*, *Cleistanthus collinus*, *Lannea coromandelica*, *Terminalia paniculata*, *Lagerstroemia parviflora*, *Mallotus philippinensis* and *Xylia xylocarpa*	511
	4. Littoral and swamp forest	84.61	6.41	8.98	*Avicennia marina*, *Excoecaria agallocha*, *Avicennia officinalis*, *Aegiceras alba* and *Dalbergia sissoo*	102
II. Dry tropical forest	5. Tropical dry deciduous forest	81.36	14.63	4.01	*Tectona grandis*, *Shorea robusta*, *Anogeissus latifolia*, *Terminalia crenulata*, *Lannea coromandelica*, *Lagerstroemia parvifora*, *Chloroxylon swietenia*, *Butea monosperma*, *Cleistanthus collinus* and *Diospyros melanoxylon*	571
	6. Tropical thorn forest	75.31	13.11	11.58	*Anogeissus latifolia*, *Albizia amara*, *Chloroxylon swietenia*, *Hardwickia binata* and *Canthium decoccum*	201
	7. Tropical dry evergreen forest	94.44	0	5.56	*Albizia amara*, *Syzygium montanum*, *Anogeissus latifolia*, *Premna tomentosa* and *Canthium dicoccum*	69
III. Montane sub-tropical forest	8. Sub tropical broad-leaved hill forest	77.44	18.91	3.65	*Schima wallichii*, *Castanopsis* species, *Pinus kesiya*, *Quercus* species and *Alnus nepalensis*	130
	9. Subtropical pine forest	92.65	6.33	1.02	*Pinus roxburghii*, *Quercus leucotrichophora*, *Rhododendron arboreum*, *Lyonia ovalifolia* and *Mallotus philippinensis*	166
	10. Subtropical dry evergreen forest					
IV. Montane temperate forest	11. Montane wet temperate forest	100.00	0	0	*Alnus nepalensis*, *Castanopsis* species, *Quercus* species, *Symplocos laurina* and *Michelia* species	67
	12. Himalayan moist temperate forest	98.66	0.67	0.67	*Quercus leucotrichophora*, *Pinus roxburghii*, *Rhododendron arboreum*, *Lyonia ovalifolia* and *Pinus excelsa*	156
	13. Himalayan dry temperate forest	100.00	0	0	*Quercus semecarpifolia*, *Pinus excels*, *Abies pindrow*, *Cedrus deodara* and *Abies smithiana*	22
V. Subalpine forest	14. Subalpine forest	98.90	1.10	0	*Abies densa*, *Abies pindrow*, *Pinus excels*, *Quercus semecarpifolia* and *Quercus* species	45
VI. Alpine Scrub	15. Moist-alpine scrub	98.39	0	1.61	*Pinus excelsa*, *Quercus* species, *Rhododendron arboreum*, *Alnus nepalensis* and *Phoebe* species	31
	16. Dry alpine scrub					

Based on champion and Seth (1968), *Source FSI (2015)

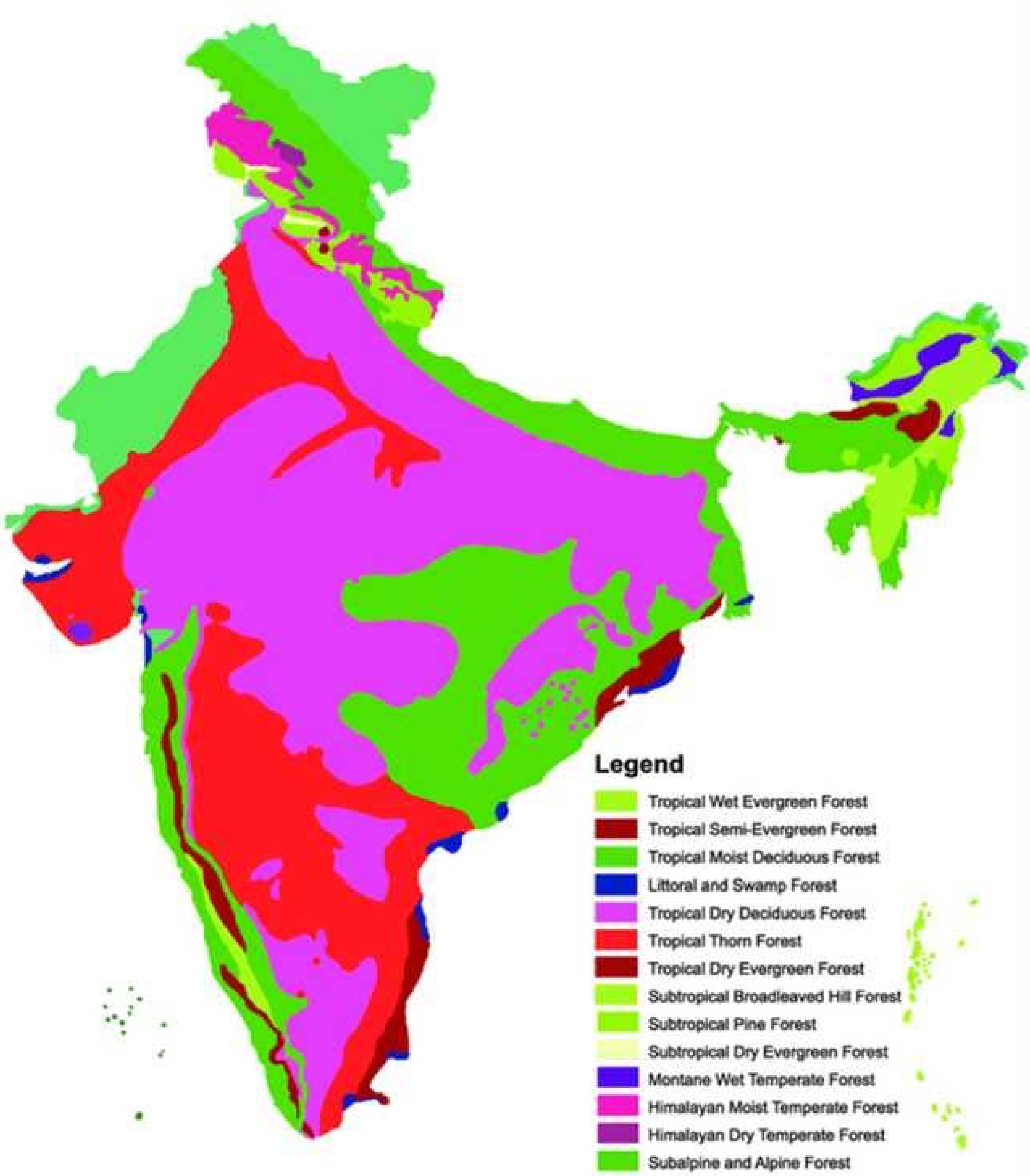

Figure 1. Forest types of India based on Champion and Seth (1968). Source (Reddy et al. 2011).

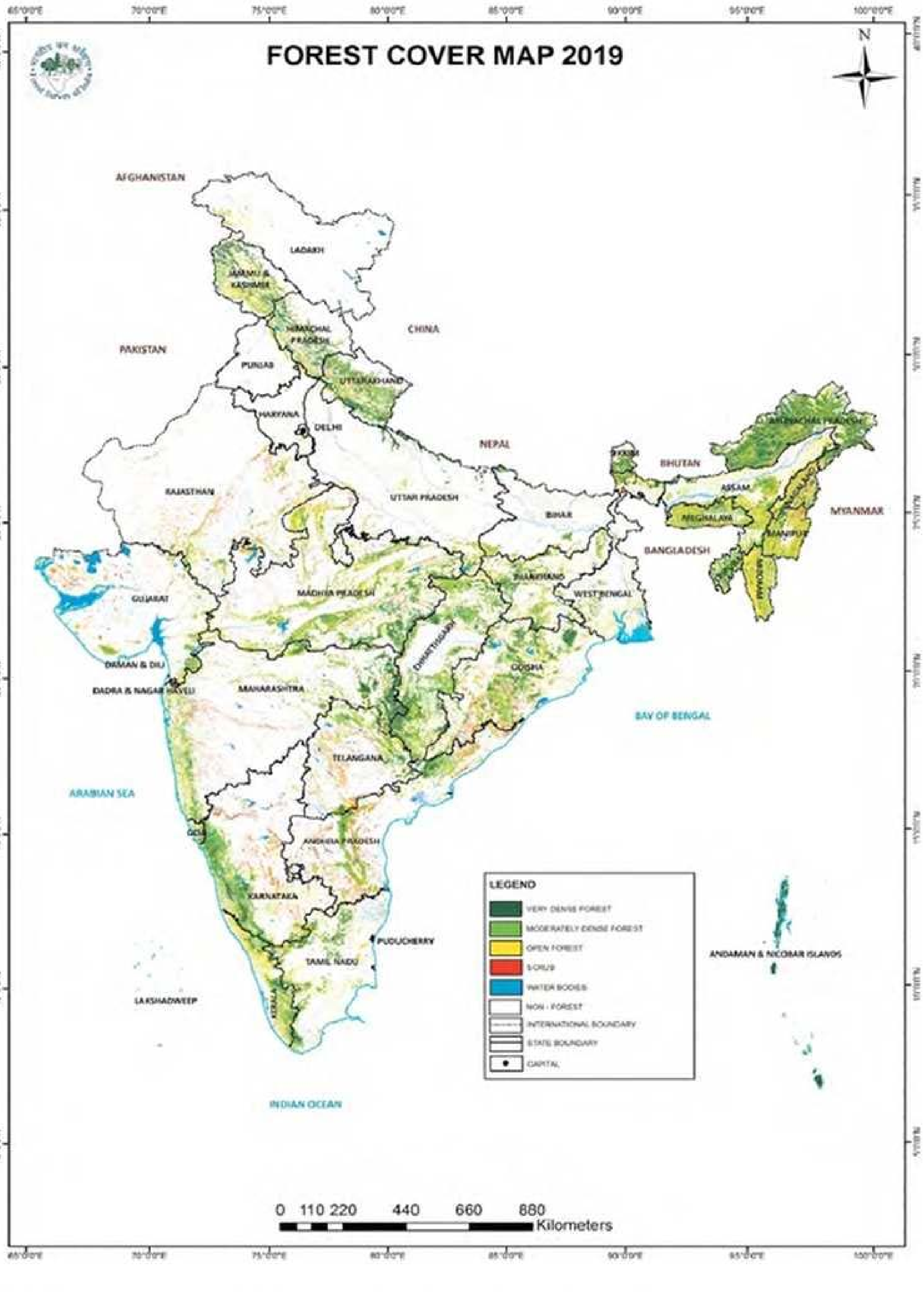

Figure 2. Forest cover map of India (Forest Survey of India 2019).

M_o is the weight of oven dried samples, G_{so} is the specific gravity of wood substance comprising the cell walls and usually 1.53 is adopted.

Historically, wood samples were taken as disks from the lower portion of bole by cutting the trees, however, most recently small increment borer samples are used as a representative of whole tree for WSG estimation. Detailed sampling design and methods used for WSG estimation in India is given in Table 2.

WSG estimation

We observed no clear relationship between WSG of the same trees recorded from different forest groups and climatic conditions, therefore, we suggest using habitat-specific WSG value for biomass estimation. Determining wood specific gravity using the disc sampling method is an old method that involves the destruction of a whole tree or a group of trees. The increment borer method of wood sampling is a simple and convenient way for wood sampling. Only a small sample of tree wood is taken without causing much damage to tree. If the core extends from the pith to the bark, it will provide a full wood sample. Larger diameter borers (12 mm) are better for core sampling as they cause less compaction, area to volume ratio is less, and larger samples are easy to handle (Williamson and Wiemann 2010). WSG value can be influenced by factors such as age class, tree height, number of sampling trees, and pith to bark variation. To reduce age related variance, samples from various girth classes should be collected and mean WSG value would be considered for the species. To reduce variation due to height, wood samples are required from different vertical profile of each tree (da Páscoa et al. 2020) (Fig. 3). Depending on the forest type, sampling 30-60 trees is adequate to stabilize the coefficient of variation in WSG (Savannah woodland- 29, Evergreen dry forest- 37, Rain forest- 41, Semi-deciduous forest – 46 and Seasonally deciduous forest 46) (da Páscoa et al. 2020). However, Cornelissen et al. (2003) suggest minimum 5 healthy and straight individual trees for sampling (Williamson and Wiemann 2010). Njana et al. (2016) opined more than 30 samples to minimize uncertainties and to make unbiased estimates.

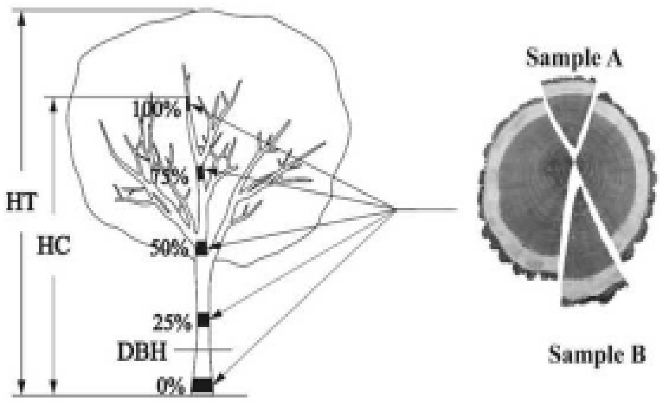

Figure 3. Schematic diagram of wood sampling location along the vertical gradient. HT denotes the total tree height, HC denotes the commercial tree height, and DHB denotes the diameter at breast height (1.3 m above ground) (da Páscoa et al. 2020).

Cores that range from pith to bark have the most accurate estimates of WSG because it incorporates all radial variation (Wiemann and Williamson 2013) However, obtaining a core sample of pith to bark for larger diameter trees, denser wood trees and trees with hollow or rotten centers is not always feasible. In such cases approximation method can be used (Williamson and Wiemann 2010, Wiemann and Williamson 2013). It requires a tree core sample of distance of 1/3 of the radius or 1/6 of DBH from bark to pith. However, it is preferable method only if tree cross section is symmetrical and pattern of WSG with distance from pith to bark is linear. If radial variance is unknown, a complete pith to bark core is divided into parts and area-weighted mean of segments are taken to determine the average WSG for an individual tree (Muler-Landau 2004).

Misconception between wood specific gravity and wood density

The specific gravity of wood is defined as the density of wood relative to the density of water (which is 1.000 g cm^{-3} at 4.4°C). Therefore, WSG is unit less. Wood density, on the other hand, is the weight of a sample of wood per volume, which includes the weight of water held by the wood at any moisture content level. It is only equal to WSG at 0% moisture content and it has a unit of g cm^{-3}. Foresters standardized some specific gravity measurements to

Table 2. Sampling design and methods used for WSG estimation.

S. No.	Researcher	Sample design	Method
1	(Chaturvedi and Raghubanshi 2013)	10 saplings of each species having 1.2-5.4 m height and 3.3-9.6 cm stem diameter were considered for disc. Wood cores were collected at place where stem diameter was measured. For < 3 m high individuals, stem diameter was measured below the lowest branch and away from stem irregularities.	Volume measured by Water displacement method. Samples were dried at 80°C till constant weight. SSD = D/V
2	(Chaturvedi et al. 2012)	10 juvenile individuals of each species were considered. Stem and branches were cut into small pieces and wood samples were taken.	Volume of fresh wood samples was measured by water displacement method. For weight samples were dried at 80°C till constant weight.
3	(Jothivel 2016)	3 samples of different girth classes for each species were taken from main stem near the ground from the bark to pith of stem at CBH.	Wood sample was dried at 105±2°C for 48 hours. Maximum moisture content method by Smith (1954).
4	(Chaturvedi et al. 2010)	Wood samples were taken at 1.3 m height using stem borer.	Volume of fresh wood samples was measured by water displacement method. For weight samples were dried at 80°C till constant weight.
5	(Tambat et al. 2019)	2 wood cores were collected from each tree and three replications were taken for each species using Hagloff's increment borer.	Maximum moisture content method by Smith (1954).
6	(Chaturvedi and Raghubanshi 2015)	After removal of bark wood samples were taken using stem borer at height where diameter was measured.	Volume of fresh wood samples was measured by water displacement method. For weight samples were dried at 80°C till constant weight.
7	(Chaturvedi et al. 2011)	Wood samples were taken at 1.3 m height using stem borer.	Volume of fresh wood samples was measured by water displacement method. For weight samples were dried at 80°C till constant weight.
8	(Tamang et al. 2019)	Trees were cored at 1.37 m height for sample extraction and 3 samples/ species were taken from different girth classes and mean of 3 samples were considered as specific gravity.	Maximum moisture content method by Smith (1954).
9	(Raphy et al. 2011)	Two blocks of each species were taken and kept open at room temperature for 48 hours and then at 100°C to determine wood specific gravity under oven dry condition.	Wood specific gravity was determined by using a specific gravity module attached to a precision electronic balance.
10	(Shanavas and Kumar 2003)	Three 5 cm thick discs each cut from the base, mid and top portion of the stem and branches. For estimating the specific gravity, three samples of 2×2 cm cross section and 2.5 cm length were made from the samples of sapwood and heartwood.	Specific gravity of samples was estimated by using IS: 1708 method (BIS 1969).
11	(Sundarapandian et al. 2014)	3.2 cm DBH individual were considered. Sample of stems of 2-8 cm long and 8.9-29 cm diameter were cut from main trunk.	Volume of each sample was determined by water displacement method and basic specific gravity was calculated as oven dry weight divided by volume.
12	(Mani and Parthasarthy 2007)	Samples of stems of 5-15cm long and 1-5 cm diameter cut at the base of live branch of different stem size class were considered.	Volume of each sample was determined by water displacement method, same sample was dried at 105°C for 48 hours and basic specific gravity was calculated as oven dry weight divided by volume.

S. No.	Researcher	Sample design	Method
13	(Sheikh et al. 2011), (Mahato et al. 2019) and (Kumar et al. 2012)	Trees were cored at 1.37 m height for sample extraction and 3 samples/ species were taken from different girth classes and mean of 3 samples were considered for specific gravity.	Maximum moisture content method by Smith (1954).
14	(Sheikh et al. 2020)	Stem core samples were considered for each species	Maximum moisture content method by Smith (1954).
15	(Keduolhouvonuo and Kumar 2017)	For each tree species, 3 samples each of the cross section of main bole and branch were taken from mature trees of different girth classes & used for specific gravity calculation.	Volume of each sample was determined by water displacement method and same sample was dried in a hot air oven and specific gravity was calculated as oven dry weight divided by volume.
16	(Rai and Proctor 1986)	A disc of 5-8 cm thick from middle of main bole was considered.	Wood sample were oven dried at 85°C. Fresh volume and dry weight ratio method was used.
17	(Gupta et al. 2017)	3 wood samples per species were taken from main stem, primary branch and secondary branch. Wood sample from main stem was taken at a height of 1.37 from ground using increment borer and wood sample of branches were taken at 10 cm above the joint using wood cutter.	Volume of each sample was determined by water displacement method and same sample was dried in a hot air oven at 100±2°C and specific gravity was calculated as oven dry weight divided by volume.
18	(Meetei et al. 2015)	3 samples of Wood and bark component were collected by harvesting them	Density was determined by water displacement method as per ASTM-D 2395-93 (1995).
19	(Devi et al. 2013)	Stem core wood sample was considered.	Maximum moisture content method by Smith (1954).
20	(Wani et al. 2014)	3 trees of each species were felled and 10 cm thick disks were cut as wood samples.	Volume of each sample was determined by water displacement method and same sample was dried in a hot air oven at 103±2°C and specific gravity was calculated as oven dry weight divided by volume.
21	(Kanawjia et al. 2013)	Trees were cored at 1.37 m height for sample extraction and 3 samples/ species were taken from different girth classes and mean of 3 samples were considered as specific gravity.	Wood sample were dried at 105±2°C. Maximum moisture content method by Smith (1954).
22	(Hegde et al. 2014)	A stem disc of 1 inch width were cut at base, middle and at the top of stem from randomly selected tree of each species for the estimation of specific gravity.	Volume of each sample was determined by water displacement method and same sample was dried in a hot air oven at 70°C and specific gravity was calculated as oven dry weight divided by volume.
23	(Sunny et al. 2019)	Wood samples were prepared from the disc which was cut from the base of log of each sample.	Wood samples were dried at 102±1°C. Maximum moisture content method by Smith (1954).
24	(Sharma et al. 2019)	Trees were cut and Wood samples of 2×2 cm^2 in cross section and 6 cm length was considered for specific gravity estimation.	Green volume was determined by mercury displacement method and oven dry weight was recorded. Standard specific gravity was calculated as oven dry weight divided by volume.

Note: SSD shows stem specific gravity, D shows oven-dry mass of a section of a plant's main stem V shows volume of the same section when still fresh.

enable comparisons within and across species, all of which are based on the oven dry (101–105°C) mass of the wood, since the moisture content of wood can differ greatly. According to Williamson and Wiemann (2010), 3 types of WSG had been identified. They are:

Basic WSG = oven dry mass / green volume / density of water

Air dry WSG = oven dry mass / air dry volume at specified moisture content / density of water

Oven dry WSG = oven dry mass / oven dry volume / density of water.

However, they have reported oven dry WSG as actual WSG because mass and volume of wood sample is determined at same state. On the basis of these types, WSG values of tree species studied by authors in India are mostly mistaken (Table 3).

Table 3. Misconceptions concerning the terms "wood specific gravity" and actual terminology according to the method used in Indian studies

S. No.	Reference	Terminology used	Actual terminology according to the methods used
1	Chaturvedi and Raghubanshi (2013)	WSG	WD
2	Chaturvedi et al. (2012)	WSG	WD
3	Jothivel (2016)	WSG	Basic WSG
4	Chaturvedi et al. (2010)	WSG	WD
5	Tambat et al. (2019)	WSG	Basic WSG
6	Chaturvedi and Raghubanshi (2015)	WSG	WD
7	Chaturvedi et al. (2011)	WSG	WD
8	Tamang et al. (2019)	WSG	Basic WSG
9	Raphy et al. (2011)	Ovendry WSG	Ovendry WSG
10	Shanavas and Kumar (2003)	Ovendry WSG	Ovendry WSG
11	Sundarapandian et al. (2014)	Basic WSG	Basic WSG
12	Mani and Parthasarathy (2007)	WSG	Basic WSG
13	Sheikh et al. (2011)	WSG	Basic WSG
14	Mahato et al. (2019)	WSG	Basic WSG
15	Kumar et al. (2012)	WSG	Basic WSG
16	Sheikh et al. (2020)	WSG	Basic WSG
17	Keduolhouvonuo and Kumar (2017)	WSG	Basic WSG
18	Rai and Proctor (1986)	WSG	WD
19	Gupta et al. (2017)	WSG	Basic WSG
20	Meetei et al. (2015)	WD	WD
21	Devi et al. (2013)	WSG	Basic WSG
22	Wani et al. (2014)	WSG	Basic WSG
23	Kanawjia et al. (2013)	WSG	Basic WSG
24	Hegde et al. (2014)	WSG	WD
25	Sunny et al. (2019)	WSG	Basic WSG
26	Sharma et al. (2019)	WSG	Basic WSG

Variation in WSG values in Indian forest ecosystems

Forest group classification by Champion and Seth (1968) is based on climatic, edaphic and successional vegetations. Therefore, many species are common to some forest groups. However, it is concerning that the WSG of all species (especially dominant species as given in Table 1) found in various forest groups has not yet been recorded. As a result, we are not able to study the source of variation for most of the species across different forest groups of India. However, we have included all of the species that were recorded from various forest groups in our study to observe the significant source of variation and the factor that has more impact on WSG variation (Table 4).

We have tried to find out the highest variation in our analysis because it demonstrates the usefulness of data and greatest error in biomass calculation if they are considered. We found that *Azadirachta indica* (0.57) and *Mallotus phillippensis* (0.51) have highest variation in WSG values amongst all reported forest types for mature trees. However, it is the bare minimum for *Myrica esculenta* (0.05) and *Anacardium occidentale* (0.07). For WSG value of mature trees across different forest types *Azadirachta indica* (0.57) shows maximum difference, while *Chloroxylon swietenia* (0.03) and *Delonix regia* (0.03) has minimum variation. *Tectona grandis* (0.41) has maximum WSG variation for mature species within same forest group, while it is minimum in *Mangifera indica* (0.01). Comparing WSG value of trees at juvenile stage with respective mature trees from all reported forest groups, *Chloroxylon swietenia* (0.35) shows highest difference while it is lowest in *Lannea coromandelica* (0.21). Comparison amongst mature trees with trees at juvenile stage for same forest group shows that, *Chloroxylon swietenia*

Table 4. Wood specific gravity values of species reported from different forest types in Indian forests

S. No.	Species name	WSG	Location	Forest group	Number of samples/Sp	Source
1	*Acacia auriculiformis* A. Cunn.ex Benth	0.77±0.03	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar,W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)
		0.774±0.095	Pondicherry University, India	Tropical dry evergreen forest	2-5	(Sundarapandian et al. 2014)
		0.59±0.01	Garhwal Himalaya, Uttarakand, India	Subtropical dry evergreen forest	3	(Kanawjia et al. 2013)
		0.57	Kerala Agricultural University, Vellanikkara, Thrissur, Kerala, India	Tropical moist deciduous forest	2	(Raphy et al. 2011)
		0.507±0.118	Thiruvazhamkunnu, Palakkad district, Kerala, India	Tropical moist deciduous forest	3	(Shanavas and Kumar 2003)
		0.65	Gaighat, Sonebhadra district, U.P., India	Tropical drydeciduous forest	5	(Chaturvedi et al. 2011)
		0.64-0.69*	Sonebhadra dist., U.P., India	Tropical drydeciduous forest	10	(Chaturvedi and Raghubanshi 2013)
		0.47-0.52*	Sonebhadra dist., U.P., India	Tropical drydeciduous forest	10	(Chaturvedi et al. 2012)
2	*Acacia catechu* (L.f) Wild.	0.76±0.7	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar, W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)
		0.776±0.04	Garhwal, Himalaya	Himalayan moist temperate forest	3	(Sheikh et al. 2011)
		0.67	North western Himalaya, India	Himalayan subtropical pine forest		(Devi et al. 2013)
		0.66	Hathinala, Sonebhadra dist., U.P., India	Tropical drydeciduous forest	5	(Chaturvedi et al. 2011)
		0.65-0.72*	Sonebhadra dist., U.P., India	Tropical drydeciduous forest	10	(Chaturvedi and Raghubanshi 2013)
		0.48-0.58*	Sonebhadra dist., U.P., India	Tropical drydeciduous forest	10	(Chaturvedi et al. 2012)
3	*Aegle marmelos* (L.) Corr.	0.64±0.01	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar,W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)
		0.845±0.03	Garhwal, Himalaya	Himalayan moist temperate forest	3	(Sheikh et al. 2011)s
		0.747±0.004	Pondicherry University, India	Tropical dry evergreen forest	2-5	(Sundarapandian et al. 2014)
4	*Albizia chinensis* (Osbeck) Merril	0.56±0.04	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar,W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)
		0.69±0.01	Kolli Hills, Namakkal, Tamil Nadu, India	Tropical drydeciduous forest	3	(Jothivel 2016)
		0.55	Kohima dist., Nagaland, India	Tropical semi evergreen forest	3	(Keduolhouvonuo and Kumar 2017)
5	*Albizia lebbek* Benth	0.90±0.01	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar,W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)
		0.70±0.02	Kolli Hills, Namakkal, Tamil Nadu, India	Tropical drydeciduous forest	3	(Jothivel 2016)
		0.58±0.04	Pali-Marwar, Rajasthan, India	Tropical thorn forest	3	(Gupta et al. 2017)
		0.513±0.1	Thiruvazhamkunnu, Palakkad district,	Tropical moist deciduous forest	3	(Shanavas et al. 2003)

S. No.	Species name	WSG	Location	Forest group	Number of samples/Sp	Source
			Kerala, India			
		0.69±0.03**	Pudukottai dist., Tamil Nadu, India	Tropical dry evergreen forest	2-5	(Mani and Parthasarathy 2007)
		0.84±0.07***	Coromandel coast of Tamil Nadu, India	Tropical dry evergreen forest	2-5	(Mani and Parthasarathy 2007)
6	*Albizia odoratissima* (L.f.) Benth	0.812±0.028	Pondicherry University, India	Tropical dry evergreen forest	2-5	(Sundarapandian et al. 2014)
		0.61±0.01	Kolli Hills, Namakkal, Tamil Nadu, India	Tropical drydeciduous forest	3	(Jothivel 2016)
		0.66	Hathinala, Sonebhadra dist., U.P., India	Tropical drydeciduous forest	5	(Chaturvedi et al. 2011)
		0.61-0.69*	Sonebhadra dist., U.P., India	Tropical drydeciduous forest	10	(Chaturvedi and Raghubanshi 2013)
		0.47-0.57*	Sonebhadra dist., U.P., India	Tropical drydeciduous forest	10	(Chaturvedi et al. 2012)
		0.65±0.03**	Pudukottai dist., Tamil Nadu, India	Tropical dry evergreen forest	2-5	(Mani and Parthasarathy 2007)
7	*Albizia procera* (Roxb.) Benth.	0.67±0.02	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar,W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)
		0.83±0.02	Garhwal Himalaya, Uttarakand, India	Subtropical dry evergreen forest	3	(Kanawjia et al. 2013)
		0.75	North western Himalaya, India	Himalayan subtropical pine forest		(Devi et al. 2013)
		0.6	Kohima dist., Nagaland, India	Tropical semi evergreen forest	3	(Keduolhouvonuo and Kumar 2017)
8	*Anacardium occidentale* L.	0.49±0.01	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar, W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)
		0.559±0.014	Pondicherry University, India	Tropical dry evergreen forest	2-5	(Sundarapandian et al. 2014)
		0.560±0.02	Thiruvazhamkunnu, Palakkad district, Kerala, India	Tropical moist deciduous forest	3	(Shanavas et al. 2003)
9	*Anogeissus latifolia* (Roxb.ex DC.)Wall.ex Guill. & Perr.	0.795±0.07	Garhwal, Himalaya	Himalayan moist temperate forest	3	(Sheikh et al. 2011)
		0.51-0.72*	Sonebhadra dist., U.P., India	Tropical drydeciduous forest		(Chaturvedi et al. 2010)
		0.50±0.02	Kolli Hills, Namakkal, Tamil Nadu, India	Tropical drydeciduous forest	3	(Jothivel 2016)
		0.819±0.127	Thiruvazhamkunnu, Palakkad district, Kerala, India	Tropical moist deciduous forest	3	(Shanavas and Kumar 2003)
		0.7	Hathinala, Sonebhadra dist., U.P., India	Tropical drydeciduous forest	5	(Chaturvedi et al. 2011)
		0.68-0.74*	Sonebhadra dist., U.P., India	Tropical drydeciduous forest	10	(Chaturvedi and Raghubanshi 2013)
		0.56-0.64*	Sonebhadra dist., U.P., India	Tropical drydeciduous forest	10	(Chaturvedi et al. 2012)
10	*Artocarpus heterophyllus* Lam.	0.59±0.03	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar, W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)
		0.57±0.03	Kolli Hills, Namakkal, Tamil Nadu, India	Tropical drydeciduous forest	3	(Jothivel 2016)
		0.513±0.073	Thiruvazhamkunnu, Palakkad district, Kerala, India	Tropical moist deciduous forest	3	(Shanavas and Kumar 2003)
		0.76	Kerala Agricultural University, Vellanikkara, Thrissur, Kerala, India	Tropical moist deciduous forest	1	(Hegde et al. 2014)
11	*Azadirachta indica* A.Juss	0.21±0.02	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar,W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)

S. No.	Species name	WSG	Location	Forest group	Number of samples/Sp	Source
		0.778±0.015	Pondicherry University, India	Tropical dry evergreen forest	2-5	(Sundarapandian et al. 2014)
		0.66±0.02	Garhwal Himalaya, Uttarakand, India	Subtropical dry evergreen forest	3	(Kanawjia et al. 2013)
		0.63±0.04	Pali-Marwar, Rajasthan, India	Tropical thorn forest	3	(Gupta et al. 2017)
		0.526±0.158	Thiruvazhamkunnu, Palakkad district, Kerala, India	Tropical moist deciduous forest	3	(Shanavas and Kumar 2003)
		0.63	Gaighat, Sonebhadra dist., U.P., India	Tropical drydeciduous forest	5	(Chaturvedi et al. 2011)
		0.64-0.68*	Sonebhadra dist., U.P., India	Tropical drydeciduous forest	10	(Chaturvedi and Raghubanshi 2013)
		0.52-0.58*	Sonebhadra dist., U.P., India	Tropical drydeciduous forest	10	(Chaturvedi et al. 2012)
		0.70±0.08**	Pudukottai dist., Tamil Nadu, India	Tropical dry evergreen forest	2-5	(Mani and Parthasarathy 2007)
		0.78±0.04***	Coromandel coast of Tamil Nadu, India	Tropical dry evergreen forest	2-5	(Mani and Parthasarathy 2007)
12	*Bombax ceiba* L.	0.27±0.03	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar,W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)
		0.35±0.00	Garhwal Himalaya, Uttarakand, India	Subtropical dry evergreen forest	3	(Kanawjia et al. 2013)
		0.35	Srinagar city, Uttarakhand, India	Himalayan moist temperate forest		(Kumar et al. 2012)
13	*Cassia fistula* L.	0.67±0.03	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar, W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)
		0.812±0.00	Garhwal, Himalaya	Himalayan moist temperate forest	3	(Sheikh et al. 2011)
		0.65±0.03	Pali-Marwar, Rajasthan, India	Tropical thorn forest	3	(Gupta et al. 2017)
		0.615±0.155	Thiruvazhamkunnu, Palakkad district, Kerala, India	Tropical moist deciduous forest	3	(Shanavas and Kumar 2003)
		0.64	Hathinala, Sonebhadra dist., U.P., India	Tropical drydeciduous forest	5	(Chaturvedi et al. 2011)
		0.61-0.67*	Sonebhadra dist., U.P., India	Tropical drydeciduous forest	10	(Chaturvedi and Raghubanshi 2013)
		0.51-0.56*	Sonebhadra dist., U.P., India	Tropical drydeciduous forest	10	(Chaturvedi et al. 2012)
		0.64±0.17**	Pudukottai dist., Tamil Nadu, India	Tropical dry evergreen forest	2-5	(Mani and Parthasarathy 2007)
		0.75±0.06***	Coromandel coast of Tamil Nadu, India	Tropical dry evergreen forest	2-5	(Mani and Parthasarathy 2007)
14	*Ceiba pentandra* L.	0.36±0.02	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar,W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)
		0.263	Thiruvazhamkunnu, Palakkad district, Kerala, India	Tropical moist deciduous forest	3	(Shanavas and Kumar 2003)
		0.28	Kerala Agricultural University, Vellanikkara, Thrissur, Kerala, India	Tropical moist deciduous forest	1	(Hegde et al. 2014)
15	*Chloroxylon swietenia* DC	0.79±0.02	Kolli Hills, Namakkal, Tamil Nadu, India	Tropical drydeciduous forest	3	(Jothivel 2016)
		0.47-0.54*	Sonebhadra dist., U.P., India	Tropical drydeciduous forest	10	(Chaturvedi et al. 2012)
		0.82±0.16**	Pudukottai dist., Tamil Nadu, India	Tropical dry evergreen forest	2-5	(Mani and Parthasarathy 2007)
		0.69±0.04***	Coromandel coast of Tamil Nadu, India	Tropical dry evergreen forest	2-5	(Mani and Parthasarathy 2007)
16	*Dalbergia sissoo* Roxb.ex DC	0.68±0.05	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar,W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)

S. No.	Species name	WSG	Location	Forest group	Number of samples/Sp	Source
		0.683±0.02	Garhwal, Himalaya	Himalayan moist temperate forest	3	(Sheikh et al. 2011)
		0.56	Andreta, Himachal Pradesh, India	Sub alpine and alpine forest	3	(Sunny et al. 2019)
17	*Delonix regia* (Bojer ex Hook.) Raf.	0.63±0.04	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar, W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)
		0.60±0.02	Garhwal Himalaya, Uttarakand, India	Subtropical dry evergreen forest	3	(Kanawjia et al. 2013)
		0.233	Thiruvazhamkunnu, Palakkad district, Kerala, India	Tropical moist deciduous forest	3	(Shanavas and Kumar 2003)
18	*Emblica officinalis* Gaertner.	0.78±0.03	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar,W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)
		0.66±0.07	Kolli Hills, Namakkal, Tamil Nadu, India	Tropical drydeciduous forest	3	(Jothivel 2016)
		0.615	Thiruvazhamkunnu, Palakkad district, Kerala, India	Tropical moist deciduous forest	3	(Shanavas and Kumar 2003)
		0.65	Kohima dist., Nagaland, India	Tropical semi evergreen forest	3	(Keduolhouvonuo and Kumar 2017)
		0.61	Hathinala, Sonebhadra dist., U.P., India	Tropical drydeciduous forest	5	(Chaturvedi et al. 2011)
		0.66-0.72*	Sonebhadra dist., U.P., India	Tropical drydeciduous forest	10	(Chaturvedi and Raghubanshi 2013)
		0.53-0.58*	Sonebhadra dist., U.P., India	Tropical drydeciduous forest	10	(Chaturvedi et al. 2012)
19	*Ficus religiosa* L.	0.51±0.02	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar, W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)
		0.652±0.064	Pondicherry University, India	Tropical dry evergreen forest	2-5	(Sundarapandian et al. 2014)
		0.67±0.02	Kolli Hills, Namakkal, Tamil Nadu, India	Tropical drydeciduous forest	3	(Jothivel 2016)
20	*Grevillea robusta* A. Cunn.ex R.Br.	0.30±0.40	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar,W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)
		0.70±0.01	Garhwal Himalaya, Uttarakand, India	Subtropical dry evergreen forest	3	(Kanawjia et al. 2013)
		0.461±0.031	Thiruvazhamkunnu, Palakkad district, Kerala, India	Tropical moist deciduous forest	3	(Shanavas and Kumar 2003)
21	*Lannea coromandelica* (Houtt.) Merr. L.	0.46±0.02	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar,W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)
		0.467±0.03	Garhwal, Himalaya	Himalayan moist temperate forest	3	(Sheikh et al. 2011)
		0.52	Hathinala, Sonebhadra dist., U.P., India	Tropical drydeciduous forest	5	(Chaturvedi et al. 2011)
		0.45-0.52*	Sonebhadra dist., U.P., India	Tropical drydeciduous forest	10	(Chaturvedi and Raghubanshi 2013)
		0.35-0.41*	Sonebhadra dist., U.P., India	Tropical drydeciduous forest	10	(Chaturvedi et al. 2012)
		0.46±0.08**	Pudukottai dist., Tamil Nadu, India	Tropical dry evergreen forest*****	2-5	(Mani and Parthasarathy 2007)
		0.56±0.003***	Coromandel coast of Tamil Nadu, India	Tropical dry evergreen forest	2-5	(Mani and Parthasarathy 2007)
22	*Mallotus phillippensis* Lam.	0.44±0.03	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar, W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)
		0.649±0.01	Garhwal, Himalaya	Himalayan moist temperate forest	3	(Sheikh et al. 2011)

S. No.	Species name	WSG	Location	Forest group	Number of samples/Sp	Source
		0.88±0.03	Kolli Hills, Namakkal, Tamil Nadu, India	Tropical drydeciduous forest	3	(Jothivel 2016)
		0.373	Thiruvazhamkunnu, Palakkad district, Kerala, India	Tropical moist deciduous forest	3	(Shanavas and Kumar 2003)
23	*Mangifera indica* L.	0.46±0.01	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar, W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)
		0.750±0.00	Garhwal, Himalaya	Himalayan moist temperate forest	3	(Sheikh et al. 2011)
		0.703±0.076	Pondicherry University, India	Tropical dry evergreen forest	2-5	(Sundarapandian et al. 2014)
		0.57±0.01	Kolli Hills, Namakkal, Tamil Nadu, India	Tropical drydeciduous forest	3	(Jothivel 2016)
		0.454	Thiruvazhamkunnu, Palakkad district, Kerala, India	Tropical moist deciduous forest	3	(Shanavas and Kumar 2003)
24	*Melia azedarach* L.	0.66±0.03	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar,W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)
		0.691±0.01	Garhwal, Himalaya	Himalayan moist temperate forest	3	(Sheikh et al. 2011)
		0.58±0.02	Kolli Hills, Namakkal, Tamil Nadu, India	Tropical drydeciduous forest	3	(Jothivel 2016)
25	*Memecylon umbellatum* Burm.f.	0.49±0.19	Kolli Hills, Namakkal, Tamil Nadu, India	Tropical drydeciduous forest	3	(Jothivel 2016)
		0.64±0.13**	Pudukottai dist., Tamil Nadu, India	Tropical dry evergreen forest	2-5	(Mani and Parthasarathy 2007)
		0.79±0.03***	Coromandel coast of Tamil Nadu, India	Tropical dry evergreen forest	2-5	(Mani and Parthasarathy 2007)
26	*Moringa oleifera* Lam.	0.54±0.03	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar, W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)
		0.275±0.01	Garhwal, Himalaya	Himalayan moist temperate forest	3	(Sheikh et al. 2011)
		0.28±0.03	Kolli Hills, Namakkal, Tamil Nadu, India	Tropical drydeciduous forest	3	(Jothivel 2016)
27	*Myrica esculenta* Buch.-Ham. Ex D. Don	0.737±0.03	Garhwal, Himalaya	Himalayan moist temperate forest	3	(Sheikh et al. 2011)
		0.737	Garhwal Himalay	Himalayan moist temperate forest	3	(Sheikh et al. 2020)
		0.7	Kohima dist., Nagaland, India	Tropical semi evergreen forest	3	(Keduolhouvonuo and Kumar 2017)
		0.68±0.23	Garhwal, Uttarakhand, India	Himalayan moist temperate forest	3	(Mahato et al. 2019)
28	*Pinus roxburghii* Sargent	0.632±0.08	Garhwal, Himalaya	Himalayan moist temperate forest	3	(Sheikh et al. 2011)
		0.632	Garhwal Himalaya	Himalayan moist temperate forest	3	(Sheikh et al. 2020)
		0.47	North western Himalaya, India	Himalayan subtropical pine forest		(Devi et al. 2013)
		0.632	Garhwal Himalaya, India	Himalayan moist temperate forest		(Nautiyal and Singh 2013)
		0.72±0.11	Garhwal, Uttarakhand, India	Himalayan moist temperate forest	3	(Mahato et al. 2019)
29	*Pongamia pinnata* (L.) Pierre	0.73±0.04	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar, W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)
		0.83±0.03	Kolli Hills, Namakkal, Tamil Nadu, India	Tropical drydeciduous forest	3	(Jothivel 2016)
		0.55±0.04	Pali-Marwar, Rajasthan, India	Tropical thorn forest	3	(Gupta et al. 2017)
		0.383	Thiruvazhamkunnu, Palakkad district, Kerala, India	Tropical moist deciduous forest	3	(Shanavas and Kumar 2003)
		0.82±0.15**	Pudukottai dist., Tamil Nadu, India	Tropical dry evergreen forest	2-5	(Mani and Parthasarathy 2007)
30	*Quercus*	0.865±0.02	Garhwal, Himalaya	Himalayan moist temperate forest	3	(Sheikh et al. 2011)

S. No.	Species name	WSG	Location	Forest group	Number of samples/Sp	Source
	leucotrichophora A. Camus	0.74	North western Himalaya, India	Himalayan subtropical pine forest		(Devi et al. 2013)
		0.865	Garhwal Himalaya	Himalayan moist temperate forest		(Sheikh et al. 2020)
		0.72±0.14	Garhwal, Uttarakhand, India	Himalayan moist temperate forest	3	(Mahato et al. 2019)
31	*Syzygium cuminii* (L) Skeeks	0.30±0.03	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar, W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)
		0.669±0.02	Garhwal, Himalaya	Himalayan moist temperate forest	3	(Sheikh et al. 2011)
		0.61±0.04	Kolli Hills, Namakkal, Tamil Nadu, India	Tropical drydeciduous forest	3	(Jothivel 2016)
		0.530±0.202	Thiruvazhamkunnu, Palakkad district, Kerala, India	Tropical moist deciduous forest	3	(Shanavas and Kumar 2003)
		0.58±0.03**	Pudukottai dist., Tamil Nadu, India	Tropical dry evergreen forest	2-5	(Mani and Parthasarathy 2007)
		0.64±0.05***	Coromandel coast of Tamil Nadu, India	Tropical dry evergreen forest	2-5	(Mani and Parthasarathy 2007)
32	*Tectona grandis* L.f.	0.85±0.04	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar,W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)
		0.684±0.094	Pondicherry University, India	Tropical dry evergreen forest	2-5	(Sundarapandian et al. 2014)
		0.523-0.774*	Sonebhadra dist., U.P., India	Tropical drydeciduous forest	10	(Chaturvedi & Raghubanshi, 2015)
		0.769-0.774	Sonebhadra dist., U.P., India	Tropical drydeciduous forest	10	(Chaturvedi & Raghubanshi, 2015)
		0.44	Kerala Agricultural University, Vellanikkara, Thrissur, Kerala, India	Tropical moist deciduous forest	1	(Hegde et al. 2014)
33	*Terminalia bellerica* (Gaertn.) Roxb.	0.42±0.03	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar, W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)
		0.48±0.01	Garhwal Himalaya, Uttarakand, India	Subtropical dry evergreen forest	3	(Kanawjia et al. 2013)
		0.534	Thiruvazhamkunnu, Palakkad district, Kerala, India	Tropical moist deciduous forest	3	(Shanavas and Kumar 2003)
34	*Toona ciliata* M.Roem.	0.64±0.05	Uttar Banga Krishi Vishwavidyalaya, Cooch Behar,W.B, India	Tropical moist deciduous forest	3	(Tamang et al. 2019)
		0.554±0.03	Garhwal, Himalaya	Himalayan moist temperate forest	3	(Sheikh et al. 2011)
		0.60±0.05	Kolli Hills, Namakkal, Tamil Nadu, India	Tropical drydeciduous forest	3	(Jothivel 2016)

*Wood specific gravity (WSG) of trees at juvenile stage, ** WSG reported from inland region of tropical dry-evergreen forest and *** WSG reported from coastal region of tropical dry-evergreen forest.

Table 5. Maximum difference of wood specific gravity value of the species reported from same forest group, different forest group and juvenile trees.

Name of species	1	2	3	4	5
Acacia auriculiformis A. Cunn.ex Benth	0.20	0.18	0.20	0.30	0.18
Acacia catechu (L.f) Wild.	0.10	0.10	-	0.29	0.18
Aegle marmelos (L.) Corr.	0.205	0.205	-	-	-
Albizia chinensis (Osbeck) Merril	0.13	0.13	-	-	-
Albizia lebbek Benth	0.39	0.32	0.39	-	-
Albizia odoratissima (L.f.) Benth	0.20	0.20	0.05	0.34	0.19
Albizia procera (Roxb.) Benth.	0.23	0.23	-	-	-
Anacardium occidentale L.	0.07	0.06	0.07	-	-
Anogeissus latifolia (Roxb.ex DC.) Wall.ex Guill. & Perr.	0.31	0.31	-	0.30	0.14
Artocarpus heterophyllus Lam.	0.25	0.19	0.25	-	-
Azadirachta indica A.Juss	0.57	0.57	0.31	0.26	0.11
Bombax ceiba L.	0.08	0.08	-	-	-
Cassia fistula L.	0.20	0.20	0.11	0.30	0.13
Ceiba pentandra L.	0.10	0.10	0.10	-	-
Chloroxylon swietenia DC	0.13	0.03	0.13	0.35	0.32
Dalbergia sissoo Roxb.ex DC	0.12	0.12	-	-	-
Delonix regia (Bojer ex Hook.) Raf.	0.40	0.03	0.40	-	-
Emblica officinalis Gaertner.	0.17	0.17	0.17	0.25	0.13
Ficus religiosa L.	0.16	0.16	-	-	-
Grevillea robusta A.Cunn.ex R.Br.	0.40	0.40	0.16	-	-
Lannea coromandelica (Houtt.) Merr. L.	0.10	0.10	0.10	0.21	0.27
Mallotus phillippensis Lam.	0.51	0.51	0.07	-	-
Mangifera indica L.	0.30	0.30	0.01	-	-
Melia azedarach L.	0.11	0.11	-	-	-
Memecylon umbellatum Burm.f.	0.30	0.30	0.15	-	-
Moringa oleifera Lam.	0.27	0.27	-	-	-
Myrica esculenta Buch.-Ham. Ex D. Don	0.05	0.05	0.03	-	-
Pinus roxburghii Sargent	0.25	0.25	0.09	-	-
Pongamia pinnata (L.) Pierre	0.45	0.45	0.35	-	-
Quercus leucotrichophora A. Camus	0.14	0.12	0.14	-	-
Syzygium cuminii (L) Skeeks	0.36	0.36	0.23	-	-
Tectona grandis L.f.	0.41	0.17	0.41	0.33	0.15
Terminalia bellerica (Gaertn.) Roxb.	0.11	0.06	0.11	-	-
Toona ciliata M.Roem.	0.09	0.09	-	-	-

1 - maximum difference in reported WSG value of mature species across all forest groups,

2 - maximum difference in reported WSG value of mature species between different forest groups,

3 - maximum difference in reported WSG value of mature species within same forest group,

4 - maximum difference between WSG value of mature trees with trees at juvenile stage, and

5 - maximum difference between WSG value of juvenile trees from their mature trees from same forest groups.

(0.32) has maximum difference in WSG value and it is minimum in *Azadirachta indica* (0.11) (Table 5).

DISCUSSION

In India, a number of studies (Salunkhe et al. 2014, 2016, Raha et al. 2020) conducted for biomass estimation have not considered habitat specific WSG value for each species. They have used WSG or wood density value from regional, or global wood density data base (Zanne et al. 2009) or from studies of different authors and neglected the effect of WSG value in biomass estimation. WSG is the primary variable for the estimation of biomass in order to assess carbon stock (Kanawjia et al. 2013). However, Zanne et al. (2009) database, like many others, is a metafile compiled from many contributors whose methodologies for WSG determinations are likely to differ (Williamson and Wiemann 2010) and whose trees may not be representative of the local flora (Wiemann and Williamson 2013). It was previously reported that use of such repositories (Zanne et al. 2009) can lead to an over estimation of WSG of approximately 16% for the species community and carbon stock up to 5 Mg/ha (Ramananantoandro et al. 2015).

Most common error in biomass estimation is the choice of inappropriate method for WSG estimation. A number of studies have not considered the pith to bark variation, tree height variation (Mani and Parthsarathy 2007, Sheikh et al. 2011, Chaturvedi and Raghubanshi 2015, Mahato et al. 2019, Tamang et al. 2019). However, some of them have considered the age class variation and sampled 3 trees of different girth classes/species (Sheikh et al. 2011, Kanawjia et al. 2013, Jothivel 2016, Tamang et al. 2019). It is already reported that WSG increases from pith to bark (Wiemann and Williamson 1988, Fimbel and Sjaastad 1994), decreases from pith to bark, constant from pith to bark (Wiemann and Williamson 2012), decreases from pith then increases to bark (Schüller et al. 3013), increases from pith then decreases to bark (Wiemann and Williamson 2012). Also the WSG value varies with variation in tree height (Beaudoin et al. 1992, Gartner et al. 2002, da Páscoa et al. 2020) and age class (Chaturvedi and Raghubanshi 2015).

Another error in biomass estimation by many workers in India is the use of wood density as WSG. Here the source of error comes from oven drying wood. Oven drying requires 101-105 °C temperature because wood contains bound water in addition to free water and all bound water cannot be driven off at less than 100 °C temperature (Williamson and Wiemann 2010). WSG and wood density calculation use two moisture content states i.e. one for mass (in the numerator) and one for volume (in the denominator). Wood volume varies according to the moisture content because wood shrinks as it dries (Williamson and Wiemann 2010). Shrinkage from green to oven dry varies from about 4% (in *Tectona grandis*) to 20% (in African ebony, *Diospyros* sp.) (Forest product laboratory, 1999). WSG value changes with moisture leading to inaccuracies in biomass estimation. Conceptually, only oven dries WSG is the true where mass and volume are determined with wood in the same state. However, basic WSG closely corresponds to an ecological trait because it is the dry biomass in a unit volume of green wood (Williamson and Wiemann 2010).

Gupta et al. (2017) reported an alternative sampling method for WSG estimation which states that primary and secondary branch sections can be used for WSG estimation avoiding core sampling or cutting the whole tree. They also reported a linear relationship in WSG of primary and secondary branches. However, it was previously reported that, branch wood is extremely variable and its relation to trunk wood is species specific and often individual specific (Okai et al. 2004, Van Gelder et al. 2006, Swenson and Enquist 2008, Patino et al. 2009). It's unlikely to reflect the variety found in tree trunks. Furthermore, juvenile wood in young branches and tension/ compression wood in older branches may have a significant impact on the WSG of branch wood. Obtaining 'clean' branch samples can be difficult, and it varies with species, individual trees, and branches (Williamson and Wiemann 2010).

Comparative analyses of common species distributed in different forest groups do not show a generalized trend for WSG. However, on the basis of values of WSG of same species distributed in different forest groups, WSG in general, tends to be higher in Himalayan moist temperate forests except a few variations. It appears that physiological dryness (cold condition) may be one of the factors for higher WSG as compared to the physical dryness. However, it is not a hard and fast rule as in a few cases some trees species in tropical moist forest have been reported to possess higher WSG.

Result of the present study envisages that forest group has no bearing on WSG value of trees. Comparing the maximum difference in WSG values found from same forest group and other forest groups, we found that about 50% of the tree species reported from the same forest group show more variation than respective tree species reported from other forest groups and vice versa. However, by comparing maximum difference in WSG values of juvenile trees with maximum difference in WSG value of mature trees across all forest groups, we found that juvenility has greater bearing on WSG variation than climate (Table 5). Similar age related effects on WSG has been reported by Chaturvedi et al. (2012) in tropical dry deciduous forest of central India.

Kanawjia et al. (2013) found higher WSG in shrubs than trees. They suggested that shrubs, being smaller woody plants, have lower moisture content than trees, resulting in higher specific gravity in shrub species. However, Martínez-Cabrera et al. (2009) did not observe differences in wood density in two groups of 65 shrub species and 135 tree species in Argentina, Mexico and the USA did not show any difference in wood density value.

Impact of climatic conditions of WSG has been reported in Brazilian forests (Fearnside 1997). However, in our study we found that WSG values of trees found in same climatic condition do not show similar or nearly similar WSG value. Further, the location of the wood sample within a tree, the geographic range of the tree species and site conditions of trees can also cause variation in wood specific gravity (Keduolhouvonuo and Kumar 2017). Variation in WSG of a species distributed in hilly terrains and tropical and subtropical areas, have been attributed to change in soil fertility, rainfall, seasonality and temperature (Sheikh et al. 2011).They reported that the average WSG of upper elevations is 9.6% greater than that at lower elevation which may be due to variation in mean annual rainfall. A positive correlation between WSG and precipitation was reported by Mani and Parthasarathy (2007). They have considered coastal site and inland site for their study to reveal the effect of precipitation on WSG value. Study showed higher mean WSG at coastal sites where precipitation was 33.4% higher than the inland site. Also the temperature was 1°C higher in inland site than coastal site, which may be another factor for WSG variation. WSG increases with increase in altitudes (Culmsee et al. 2010) on account of low soil moisture and nutrients (Mahato et al. 2019). According to Gupta et al. (2017), WSG varies significantly among species and sampling locations within the individuals of species. Hegde et al. (2014) studied different physical properties of wood in some tropical tree species of south India and reported that low ash content may be a reason for low WSG value. Shanavas and Kumar (2003) studied fuel wood characteristics of trees and reported that presence of lignin and other denser fractions enhance wood density and may be a cause of inter-specific variations.

CONCLUSION

A large variation in WSG value is observed in different forest groups due to different chemical and physical properties of soil, variation in precipitation, change in climatic condition, change in elevation, change in geographical location, variation in temperature and variation in light. However, no direct relationship was found with climatic conditions. Species wise variations in WSG values are observed in same forest group may be due to the change in location. As a result, using such species specific WSG data available at local, regional and global repositories is not suitable and may result in significant biomass estimation inaccuracies. Although the review provides WSG of different tree species in all the Indian forest groups at a place, we suggest that habitat-specific WSG is the only way to be used for biomass estimation with accuracy.

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