

Assessment of Carbon Stock at Tree Level Using Terrestrial Laser Scanning Vs. Traditional Methods in Tropical Forest, India

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Abstract—Accurate assessment of carbon stock of trees is essential to model carbon dynamics in the forest ecosystem. Estimation of carbon stock at regional level involves successive quantitative modeling at various scales. While developments in airborne and satellite remote sensing has greatly reduced the uncertainty in up scaling of plot level biomass and carbon stock estimates to regional or national estimates. A substantial amount of uncertainty in the system comes when carbon stock of each tree in a plot is estimated from established allometric equations. In this study, 12 trees were destructively measured for their carbon stock value and the same was estimated using terrestrial laser scanning technique, local allometric equations, and global allometric equations. The carbon content estimates from terrestrial laser scanning method (26.01% RMSE relative to mean) were consistently closer to destructive measurements as compared to local allometric equations (42.58%–101.88% RMSE relative to mean) and global allometric equations (38.8%–50.69% RMSE relative to mean). Field measurement of sample wood density and sample carbon content significantly reduced the uncertainty in local allometric equations. The sources of error and applicability of each technique are discussed in this study.

Index Terms—Allometric equations, carbon estimation, forestry, terrestrial laser scanning.

I. INTRODUCTION

THE IMPORTANCE of monitoring carbon and vegetation biomass has been recognized by the Paris Agreement, which was signed by 197 countries, and ratified by 189 nations who have all committed to report their carbon footprint. Hence, monitoring the spatiotemporal carbon dynamics is, therefore,

Manuscript received August 31, 2020; revised October 26, 2020, December 15, 2020, January 12, 2021, and March 27, 2021; accepted April 13, 2021. Date of publication April 28, 2021; date of current version May 26, 2021. This work was supported by ISRO-IGBP under National Carbon Project. (Corresponding author: Jayant Singhal.)

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Digital Object Identifier 10.1109/JSTARS.2021.3076195

a high research priority. Accurate measurement of the carbon stock is also essential for sustainable forest management and to mitigate the greenhouse gas emissions that drive global climate change. The accuracy of these results has significant influence on the kind of carbon dynamics studies which will be possible and hence have a much larger influence on understanding of climate change. The carbon stock estimation at various scales requires application of techniques that are very scale-specific. These techniques can range from field inventories and terrestrial laser scanning (TLS) at individual tree level and plot level, airborne LiDARs, or radars at regional level and satellite remote sensing at national or global level. All the techniques have their own associated uncertainties and inaccuracies that get carry forwarded to the next level. Therefore, forest carbon stock measurement done at any scale is heavily affected by the accuracy of methods used to determine carbon stock present at individual tree level.

Allometric equations are in general used to predict the biomass/carbon stock present in a tree from easy-to-measure tree attributes such as diameter at breast height (DBH) and tree height. However, these equations are often established with trees selected for commercial logging purposes and hence only biased sample of trees gets measured, which is often unrepresentative of the total span of DBH or height or region. The biomass values measured during logging to establish such equations are made using little to no level of compartmentalization, or, in many cases, using water displacement method which further contributes to error in determination. Tree allometric equations give the statistically established most probable value of biomass (bole biomass) and not the actual biomass for the tree which can ideally be known through destructive measurements. Height measurements on the field using a hypsometer can underestimate the tree height by as much as root-mean-square error (RMSE) of 3.11 m which translates into missing 14.45% of Above Ground Biomass (AGB) when upscaled to plot level [1].

Use of airborne laser scanning has already proved to reduce error in extrapolation of plot level above ground biomass values to regional scale as compared to previously used remote sensing techniques. Stovall and Shugart [2] have shown that plot-level AGB RMSE in a mixed deciduous hardwood forest reduced from 18.5% to 9.8% when TLS-based models were used to estimate AGB of individual trees as compared to when Jenkins *et al.* [4] allometry was used. Vorster *et al.* [3] have shown that error in allometry at individual tree level can far exceed the remote

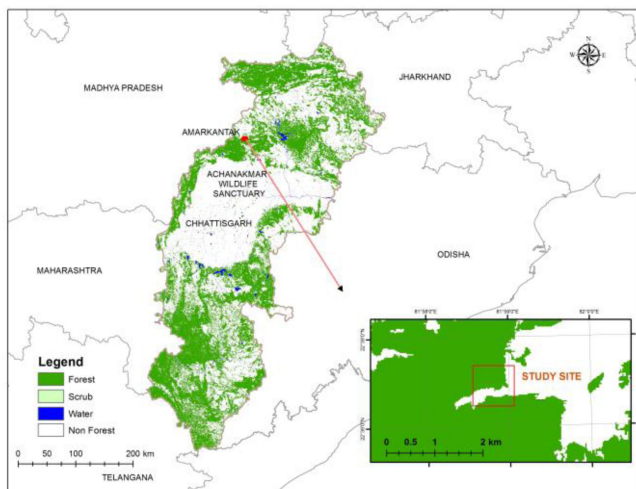


Fig. 1. Location map of study area. The study area is located in Achanakmar wildlife sanctuary present in central eastern state of Chhattisgarh, India. The map describes the extent of forests and scrubs throughout the state along with prominent water bodies.

sensing model prediction uncertainty. A study by Vorster *et al.* [3] also showed that when destructively measured AGB values for 285 trees were compared with AGB values estimated from locally derived allometric equations, Jenkins *et al.* [4] and forest inventory and analysis component ratio method (FIA-CRM) [5], the estimated RMSE came out be 46.3%, 67.4%, and 62% respectively, which is quite high.

In this study, reference grade carbon content values were calculated for 12 trees belonging to 3 species in India through destructive measurements. For the same trees, carbon content values were also calculated using both conventional techniques (using established local and global allometric equations) and nonconventional techniques (using TLS).

II. METHODS

A. Study Site

The Achanakmar–Amarkantak Biosphere Reserve (BR Declaration by UNESCO [6]) lies between $22^{\circ}15'N$ to $22^{\circ}58'N$ and $81^{\circ}25'E$ to $82^{\circ}50'E$, having an area of 3835.51 km^2 (Fig. 1). The reserve is located in the northern part of bio-geographic zone 6 and bio-geographic province 6 (Deccan peninsula and central highlands), with topography ranging from high mountains to shallow valleys and plains. Altitude varies from 200 to 1000 m from mean sea level. The daily maximum temperature ranges from 24°C to 39°C and daily minimum temperature ranges from 10°C to 25°C throughout the year, with average 1624 mm annual rainfall [7].

The forests constitute North Indian deciduous forests with subtypes of Moist Peninsular Sal Forests, Moist Mixed Deciduous Forests, Northern Dry Mixed Deciduous Forests (dominated by Sal, *Shorea robusta* Roth and co-dominated by *Anogeissus latifolia* (Roxb. ex DC.) Wall. ex Guill. & Perr., and *Lagerstroemia parviflora* Roxb.), interspersed with rain-fed fields and inhabited areas. Study site has nearly 1498 plant species [7]. According to Forest Survey of India (FSI), *S. robusta* (10.62%)

and *A. latifolia* (2.9%) represent the highest and sixth highest growing stock contributors in India's forests [8]. The sample trees (12 individuals) were selected for the TLS as well as destructive sampling based on their dominance in central Indian forest ecosystem—*S. robusta* (5), *A. latifolia* (5), and *L. parviflora* (2) individuals. These samples were part of the selection of the trees to be cut under the management of the working plan of the area, from the fringes of the transition zone of the BR.

B. Terrestrial Laser Scanning

The targeted trees were selected such that they should have minimal amount of vegetation around them to get good scans with the TLS and the trees should be filling a wide range of girth class. Before scanning the trees, the DBH and tree height of each tree were measured using diameter tape and a laser range finder (Nikon forestry pro). The trees were scanned during the January 2018 (green season) using Riegl VZ-1000 instrument.

All the 12 trees were scanned from at least four positions and at most eight positions. The trees were scanned from an optimum distance and of varying density such that the spacing between points should not exceed 2 cm if projected on a perpendicular plane. This can be easily calculated as distance of target from TLS instrument \times angular step width. This 2 cm can also be reduced for smaller trees. Efforts were made to spread out scan positions evenly in all directions. Individual scans were merged with each other using RiSCAN Pro software (<http://www.riegl.com>) with circular reflectors acting as the tie points.

C. Destructive Measurements

The field work for destructive measurements was conducted during February 2018. For felling and compartmentalization of the trees, the FAO manual was strictly followed [9]. The only difference being that from the main trunk, the samples were taken at a difference of 3 m instead of at every 2 m as directed by the manual. The tree was basically compartmentalized into trunk, main branches, scattered branches, and leaves.

Each tree was felled on a tarpaulin sheet. All of the branches still connected to the trunk were labeled and separated from the trunk. The sub-branches were then removed from the main branches. The leaves were completely removed from the tree and collected in a bag. The trunk and the main branches were sectioned into 3-m-long logs. The sub-branches that were scattered all over the tarpaulin sheet were collected in bag and labeled scattered branches. All of the logs, scattered branches, and leaves were weighed in the field itself. Samples were collected in the form of 3-cm-thick cross-sectional wood slices of trunk and branches. These wood as well as leaves samples from each tree were weighed and sealed in ziplock bags. These samples were then sent to Wood Research Institute, Bangalore, for specific gravity measurements and Institute of Forest Biodiversity (IFB), Hyderabad, for carbon content measurements. The carbon content for each compartment of each tree was measured using a CHN analyzer (Elementar vario EL cube) instrument.

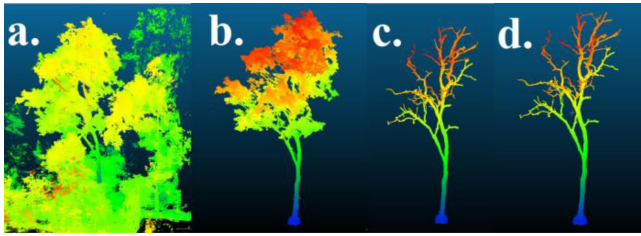


Fig. 2. Cleaning of TLS point cloud dataset. (a) Raw point cloud data of the tree. (b) Level 1 cleaning involves removal of points not associated with the target tree. (c) Level 2 cleaning involves removal of points coming from leaves and small twigs. (d) Level 3 cleaning involves application of SOR filter to remove and leftover sparse points.

D. TLS Data Processing

1) *Preprocessing*: Merged scans were exported as *.las files. These *.las files were opened in Cloudcompare software,¹ where three levels of cleaning were applied to the datasets (Fig. 2). Level 1 cleaning involved removal of all the non-tree points from the point cloud, i.e., points coming from other trees, ground, grass, and shrubs around the target tree. Level 2 cleaning involved removal of all the returns coming from leaves and very small twigs. The instrument, i.e., Riegl VZ-1000 laser scanner, has an accuracy of 8 mm under ideal conditions and hence it is assumed that accurate scanning of any twig with less than 1.6 cm diameter (i.e., 2×0.8 cm) is not possible with this instrument. Small twigs and branches also move within the same scans and between two scans due to wind. This movement itself is often many times greater than the dimensions of the twigs itself, and hence in scans, it appears as random distribution of points instead of a hollow cylinder-like distribution. Keeping the above two points in mind, the returns from leaves and twigs were discarded to minimize the uncertainties.

Level 3 cleaning involved statistical outlier removal (SOR) filter. SOR filter computes, first, the average distance of each point to its neighbors (considering k -nearest neighbors for each— k is the first parameter). Then, it rejects the points that are farther than the average distance plus a number of times the standard deviation (second parameter). This process not only removes the points that might not have been removed in level 1 and level 2 cleaning but also produces a much cleaner surface on trunk and branches. The cleaned point clouds of trees (Fig. 1.) consisted of return coming only from the trunk and branches of the tree.

A k value of 10 points and additional one standard deviation distance were used throughout this study. These parameters were set by visually inspecting the resultant point clouds.

2) *Volume Calculation*: TLS has been a blessing for deriving wood volume of trees in nondestructive fashion and many studies have been conducted in the past that were able to successfully demonstrate that but majorly by fitting cylinders [10]–[12] to subsets of the point cloud. Stoval *et al.* [13] have pointed out that cylinder fitting models do not perform well in dense or clumped trees with significant occlusion and can result in unexpected and unrealistic volumes. Also, they are prone to error when the tree structure is simply not a cylinder, i.e., buttress roots and

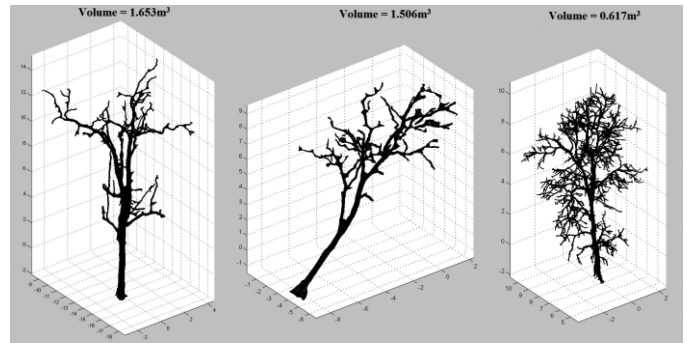


Fig. 3. The mesh generated and the calculated volume of cleaned point of a *Shorea robusta*, *Anogeissus latifolia*, and *Lagerstroemia parviflora* tree, respectively.

multiple trunks. Stoval *et al.* [13] developed a novel method which calculates trunk volume using a convex hull peeling method called outer hull method and also estimates branch and foliage volume using voxelization. The method was tested and validated by them on lodgepole pines.

To calculate the volume of the tree, the cleaned point cloud datasets were exported as ASCII files and imported in MATLAB 2019a. We wanted to fit an α -shape to each imported point cloud and calculate its enclosed volume. For this, “alphavol” package written by Jonas Lundgren available on matlab central² was used. The package has also been used to estimate the mass of extinct quadrupedal mammals from α -volume of their skeletal fossils [14]. α -Shapes essentially are parametrized generalizations of the convex hull. The α -shape fitted is not only defined by the set of points they are fitted to but also by the value of parameter alpha (α) which can range from 0 to infinity. The value of this parameter α defines how “crude” or “fine” the fitted shape will be.

In this study, we used α -shapes to completely wrap and enclose the cleaned point cloud inside a 3-D triangular mesh and volume inside the mesh considered as the wood volume. The mesh follows the surface of the tree unassumingly of any geometry and hence in tropical forests where trees often have buttresses and non-cylindrical surfaces; such methods are required not just for better volume calculation but also for better detection of stem. α -Shapes were fitted to point cloud of each tree and their volume was calculated. By visual inspection, it was found that the parameter value of 0.1 fitted the mesh perfectly to the point cloud. It was also found that in case of more complex tree structure, it was better to further segment the point cloud to reduce the complexity and apply α -shapes to segments individually, than it is to fine-tune the value of parameter to fit the mesh better. Fig. 3 shows the fitted α -shape for point cloud of *S. robusta*, *A. latifolia*, and *L. parviflora*, respectively.

E. Allometric Equations

An allometric equation is basically a regression equation between two or more related attributes of trees for a given population of tree. It is typically constructed between AGB

¹Online. [Available]: <http://www.danielgm.net/cc/>

²Online. [Available]: <https://www.mathworks.com/matlabcentral/>

TABLE I
SPECIES AND AREA SPECIFIC (FOR BILASPUR DISTRICT) ALLOMETRIC
EQUATIONS (FSI, 1996)

Sl. No	Species	Allometric Equations	Samples(n)	
1	<i>Shorea robusta</i>	$V=0.10715-1.82058D+11.91792D^2+0.49058D^3$	1306	0.95
2	<i>Anogeissus latifolia</i>	$V=-0.02958+8.05003 D^2$	332	0.48
3	<i>Lagerstroemia parviflora</i>	$V=0.06913+1.37605D+11.89119D^2$	113	0.98

D is the diameter at breast height of the tree and V is the volume of the trunk.

and DBH. These relationships can vary a lot between trees of different species and trees present in different geographical locations. In this study, the relationship established between merchantable wood volume and DBH by Forest Survey of India (FSI, 1996) [15] for different species present in different areas is considered as local allometric equations. These volume equations for Bilaspur district for *S. robusta*, *A. latifolia*, and *L. parviflora* (FSI, 1996) [15] are as follows (Table I).

By using field measured values of DBH, the merchantable wood volume of each of the 12 trees was calculated.

In this study, we consider the relationship established by Chave *et al.* [16] between AGB of tropical trees and their respective tree height, DBH, and wood-specific gravity as global allometric equation. These equations were established using a global database of directly harvested trees (4004 tree ≥ 5 cm trunk diameter) at 58 sites spanning a wide range of climatic conditions and vegetation types all across the tropics. The relationship established is as follows:

$$AGB_{est} = 0.0673 \times (\rho D^2 H)^{0.976}$$

where AGB_{est} is the AGB of the tree, ρ is the wood density in $g\ cm^{-3}$, D is DBH in cm, and H is tree height in m. This AGB relation already incorporates the wood density into it which can be both established values [17] and field measured values. By using field measured values of DBH and height of the 12 trees and using both field measured and established values of wood density [17], two sets of AGB values were calculated using global allometric equations.

F. Carbon Content of a Tree

This study compares the three fundamental methods to estimate carbon content of a tree.

- 1) Using allometric equations (both local and global allometric equations).
- 2) Using TLS.
- 3) Through destructive testing.

Here, the destructive measurements are assumed to be the most accurate and a reference to measure accuracy of other methods.

In case of destructive testing traditionally, the sample collected from the field are oven-dried for couple of weeks and its dried weight (biomass) is measured. This dried weight is multiplied with a constant carbon fraction of dry matter value of

0.47 (guidelines designed by IPCC [18]) to arrive at the carbon content of the sample which is then extrapolated (using wet weight of the sample) over the log, branch, or foliage, which it represents. The sum of carbon content of all the parts of the tree compartmentalized earlier would be considered as the carbon content of tree. Equipment today have become much more advanced and the CHN analyzer (Elementar vario EL cube) directly gives us the conversion factor from wet mass to carbon content for the sample.

In case of TLS, there is no direct measurement of wet weight. It provides wood volume of the tree, and using field-derived values of specific gravity, the wet mass of the tree is estimated. From this wet mass, using field derived values of carbon content, the carbon content of the whole tree is estimated.

This study assesses both local and global allometric equations. The local allometric equations provided us the merchantable wood volume from field-measured values of DBH. To account for nonmerchantable part of the tree, a biomass expansion factor of 1.59 is used [19]. From this value of wood volume, the carbon content of the tree can be estimated using field-derived or established values of both specific gravity [17] and carbon content [18], similar to the approach adopted by [19].

The global allometric equation gave us two sets of AGB values (using field-measured and established values of wood density) for the 12 target trees. AGB from this relation when multiplied with field measured value of carbon fraction or with a constant 0.47 (guidelines designed by IPCC [18]) gives us the carbon stock present in the tree.

So the amount of carbon present in each of the tree was calculated in six different ways described as follows.

- 1) Destructive testing

$$\text{Amount of carbon present in the tree} = \sum_{i=0}^n m_i \times C_i.$$

- 2) Terrestrial laser scanning

$$\begin{aligned} \text{Amount of carbon present in the tree} \\ = V \times \rho_f \times C_f. \end{aligned}$$

- 3) Local allometric equations with established density and carbon content values

$$\begin{aligned} \text{Amount of carbon present in the tree} \\ = f(\text{DBH}) \times K \times \rho_t \times C_t. \end{aligned}$$

- 4) Local allometric equations with field measured density and carbon content values

$$\begin{aligned} \text{Amount of Carbon present in the tree} \\ = f(\text{DBH}) \times K \times \rho_f \times C_f. \end{aligned}$$

- 5) Global equation with established density and carbon content values

$$\begin{aligned} \text{Amount of carbon present in the tree} \\ = f(\text{DBH}, h, \rho_t) \times C_t. \end{aligned}$$

TABLE II
CARBON CONTENT (CC) OF THE 12 TARGET TREES AS ESTIMATED FROM SIX DIFFERENT METHODS

Tree ID	DBH (cm)	Height (m)	Wet mass (Kg)	CC TLS (Kg)	CC FSI established values (Kg)	CC FSI field values (Kg)	CC Chave established values (Kg)	CC Chave field values (Kg)	CC destructive testing (Kg)
Sal1	44.2	14.3	1133.21	521.65	855.65	673.06	503.07	467.24	418.95
Sal2	26.4	9.4	225.78	203.22	226.53	184.98	122.08	99.06	86.65
Sal3	29.6	9.0	235.58	198.7	253.17	198.52	146.11	108.27	86.82
Sal4	32.8	12.2	397.15	282.81	431.52	356.69	239.99	245.98	145.72
Sal5	42.0	14.2	859.52	362.97	641.39	478.31	451.7	358.86	301.25
Anog1	29.3	11.81	939.57	356.56	386.83	316.55	204.18	144.68	361.37
Anog2	30.1	14.67	969.34	388.85	409.99	335.89	266.41	186.72	373.25
Anog3	32.5	12.36	906.79	322.09	479.45	371.12	261.08	190.6	329.89
Anog4	40.3	15.57	1522.73	651.33	746.75	633.85	497.9	353.73	607.47
Anog5	31.7	6.25	883.86	357.52	455.4	379.04	127.85	101.85	345.75
Lag 1	33.7	12.08	632.54	226.09	866.86	691.22	217.25	170.5	278.14
Lag 2	25.0	12.99	269.26	149.19	530.7	437.22	129.76	107.66	101.68

6) Global equation with field measured density and carbon content values

Amount of carbon present in the tree

$$= f(\text{DBH}, h, \rho_f) \times C_f$$

where m_i = mass of the compartment (logs, twigs, leaves, etc.) that the i sample represents; C_i = carbon content of sample of i ; V = wood volume of the tree as measured by TLS; DBH = field-measured diameter at breast height; $f(\text{DBH})$ = local allometric equation in which volume of bole is a function of DBH; K = biomass expansion factor; ρ_t = already established wood density value; C_t = already established carbon content value; ρ_f = field-measured wood density value; C_f = field-measured carbon content value; h = field-measured height of the tree; and $f(\text{DBH}, h, \rho) =$ global equation in which biomass is function of DBH, h , and ρ .

III. RESULTS

The carbon content for the 12 target trees were successfully estimated in nondestructive fashion using TLS point cloud. The field-measured wood density varied about 0.91 g/cm³ or 12.43% from the established wood densities for the 12 trees. The field-measured carbon content varied by about 0.092 or by 19.57% from the established value of 0.47. Biomass expansion factor (BEF) was calculated for each tree from destructive measurements as ratio of carbon stock present in the tree and carbon stock present in the bole. This destructively measured value of BEF varied by about 0.254 or by 16% from the established value of 1.59.

Carbon content estimates (Table II) for all the 12 target trees from the six methods were plotted (Fig. 4) against their respective DBH. One can observe that the local allometric equations had a tendency to overestimate the amount of carbon present in the trees. We see that use of field measured values of carbon content and wood density in case of local allometric equations lowered the estimates of carbon stock and hence improved the result. In case of *L. Parviflora*, we see that carbon content estimates from local allometric equations are giving a much higher value. We also see that of the three species, least number of trees were used to form this local allometric equation ($n =$

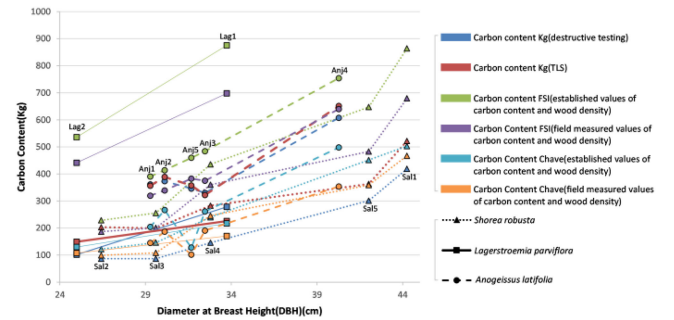


Fig. 4. Carbon content of the 12 target trees of 3 different species (represented by different symbols in the figure) as estimated from 6 different methods (represented by different colors in the figure) plotted against their respective diameter at breast height (DBH). Here, Sal refers to *Shorea robusta*, Anj refers to *Anogeissus latifolia*, and Lag refers to *Lagerstroemia parviflora*.

113 for *L. parviflora* vs. $n = 332$ for *A. latifolia* and $n = 1306$ for *S. robusta*), and hence it may not be as accurate.

The global allometric equations gave closer estimates for *S. robusta* and *L. parviflora* as compared to local allometric estimates, but not for *A. latifolia* where it gave consistently lower estimates. The use of field-measured values of carbon content and wood density in case of global allometric equation degraded the result as opposed to the case in local allometric equation. This can be due to the fact that local allometric equations were essentially relations between volume and DBH of the tree while global allometric equation [16] was relation between AGB and density, and DBH and height of the tree.

The TLS-based carbon content estimates were fairly close to the destructively measured estimates of carbon content for trees with sufficiently large DBH. The TLS-based method overestimated the carbon content present in the trees with smaller DBH. This can be explained by the fact that TLS instrument has the same accuracy for small and big trees. For example, an error of 1.6 cm is much more significant in case of tree with 25 cm DBH as compared to a tree with 45 cm DBH. Moreover, we are trying to derive volume (m³) from the instrument so the error in volume gets cubed also.

The overall RMSE relative to mean in estimation of carbon content for the 12 trees with estimates from destructive measurements considered as true value was 26.01% for TLS, 38.8%

for Chave *et al.* [16] using established values of parameters, 50.69% for Chave *et al.* [16] with field measured values of parameters, 67.81% for local allometric equations with field measured values of parameters, and 101.88% for local allometric equations with established values of parameters. Major cause of such poor performance of local allometric equations comes from the overestimation in case of *L. parviflora*. If we remove those two trees from the analysis for local allometric equations and only use *S. robusta* and *A. latifolia* data, then RMSE relative to mean reduces to much more acceptable level of 42.58% for local allometric equations with field-measured values of sample wood density and carbon content and 72.48% for local allometric equations using established values. RMSE relative to mean in this study was calculated as follows:

$$\text{RMSE relative to mean (\%)} = \frac{\sqrt{\frac{\sum_{i=1}^n (CC_{\text{actual}_i} - CC_{\text{estimated}_i})^2}{n}}}{CC_{\text{actual}}} \times 100$$

where CC stands for carbon content and destructively measured values were considered as actual values.

IV. DISCUSSION

The high RMSE relative to mean values reported here is not the effect of accuracy of shape-fitting algorithm to estimate the volume of point cloud alone or the accuracy of the allometric equation in predicting merchantable wood volume or AGB alone, rather also reflects error induced by all the assumptions and generalizations made to come to a carbon stock value of a tree and also the accuracy with which tree parameters were measured and of the TLS instrument to precisely capture the 3-D geometry of the tree.

In case of destructive measurements, the trees were heavily compartmentalized and carbon content values for samples from each compartment were measured in a lab. Hence, carbon stock estimated from destructive measurements was estimated with least amount of assumptions and hence were taken as reference to compare performances of other methods.

In case of TLS and allometric equations, when a single value of carbon content and wood density is used for a particular tree, one is assuming that these values stay uniform throughout different compartments of the tree. These values vary not only within a tree but also between different trees. Assuming these values to be constant induces uncertainty in the final estimation.

BEF was used in estimation of carbon content using local allometric equations, which is not the case with global allometric equations. Local allometric equations used in this study had an advantage of being constructed for the same location and for the same species, while global allometric equations used in this study was a pan tropical equation and same for all species. Global allometric equations used in this had advantage over local allometric equation of incorporating wood density and tree height within it. However, by comparing even the best RMSE relative to mean of 42.58% in case of local allometric equations to that of 38.8% for the global allometric equations, one can safely conclude that whatever advantage that local allometric equations had of being area- and species-specific was totally

nullified by the use of BEF and not incorporation of tree height and wood density in the regression equation.

One should also note that in local allometric equation for *L. parviflora*, $n = 113$ might seem statistically significant but these equations are often constructed from trees undergoing commercial logging and do not span a wide range of CBH. Hence, these relations can give huge error when estimating wood volume of trees whose CBH are out of the span of CBHs with which these equations were constructed. One can see that local allometric equation for *A. latifolia* will return negative values of volume for very small values of DBH and also its R^2 value at 0.48 is quite low, indicating that it was probably regressed with a small span of values of DBH that were far away from zero.

While allometric equations give us the statistically most probable value of wood volume or AGB, the actual values for individual trees will vary slightly from it. In case of TLS, we are capturing the shape and structure of every tree individually, and hence this type of error is not present in the TLS method. That is why TLS method performed better than allometric equations in estimating carbon content of individual trees.

One should also note that for establishment of even local allometric equations, the trees were destructively logged. TLS can be used to provide reference wood volume values for establishment of such allometric equations without destroying the sample trees. Such equations will also be free from error induced by use of BEF.

Going by the performance of each method in this study, the following order of preference for methods must be used for accurate carbon stock estimation at tree:

- 1) destructive measurements;
- 2) TLS method;
- 3) global allometric equations with established values of carbon content and wood density; and
- 4) local allometric equations with field-measured values of carbon content and wood density.

Overall, for the 12 trees, global allometric equation without the use of field-measured carbon content and wood density value outperformed local allometric equations with field-measured values of carbon content and wood density, but for only *A. latifolia*, the latter gave better results. So if field-measured values of carbon content and wood density are available, one must also consider the carbon stock estimates of local allometric equations along with that of global allometric equations. There is no point in using the remaining two methods not listed above.

V. CONCLUSION

The following research areas in the field of carbon and biomass monitoring of forests need to be emphasized to address the Paris Agreement effectively: (1) Exploring novel techniques (e.g., LiDAR) across a range of spatiotemporal scales to gain new insights into forest 3-D structure; (2) Utilizing near-continuous observations from new and improved satellites to capture the subtle variations of forests; (3) Developing algorithms that are specifically designed to meet diverse forest conditions and coupling remote sensing observations with process-based models to improve our understanding of forest carbon dynamics and for long-term projections. From the present study, we draw the

following conclusions and make contribution toward broader objective of the Paris Agreement.

- 1) There exists difference in allometric estimates of carbon stock of tropical trees. In some cases, local allometric equations give closer results, and in some cases, global allometric equations give better results.
- 2) TLS can give estimates of wood volume and amount of carbon present in a tree in a nondestructive fashion. TLS overestimated the volume for small trees due to known reasons, but for sufficiently big trees, the TLS-derived estimates are fairly close to destructively measured estimates of carbon stock.
- 3) Allometric estimates of volume give a statistically most probable value of wood volume of trees of that particular species. TLS, on the other hand, gives us the wood volume of the particular target tree and hence performs more consistently when a target tree is in question.
- 4) Having field-measured values of wood density and carbon content always improves the accuracy of the final carbon stock estimates in case of volume–DBH allometric relations as compared to use of historically established values.
- 5) TLS can be used to establish local allometric equations, that too without destructively logging of the trees.

ACKNOWLEDGMENT

This work was supported under ISRO-IGBP-NCP Project. The authors would like to thank their gratitude to Director, National Remote Sensing Centre, Hyderabad for his guidance and facilities. Further, they would like to acknowledge Marwahi Division, Chhattisgarh Forest Department for their logistical support to make this study a success.

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