Drewno 2014, Vol. 57, No. 192
DOI: 10.12841/wood.1644-3985.S01.08

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ESTIMATING FOREST BIOMASS BY REMOTE SENSING RADAR DATA IN BRAZIL

Remote sensing-radar was used to analyze forest mapping and biomass estimates on Brazilian territory. Two examples of SAR attributes for the modeling of the aboveground biomass of forest stands are presented: (1) full-polarimetric attributes of PALSAR/ALOS (Phased Array type L-band Synthetic Aperture Radar/ Advanced Land Observing Satellite) for modeling in the Amazonian tropical forest, considering the influence of the geomorphometric aspects on this radar response, and (2) polarimetric and interferometric airborne data (X_{HH} *and full-polarimetric of P-band) for modeling Eucalyptus sp. stands. In both cases, an analysis of forest structure variability through polarimetric signatures was conducted. A multivariate regression technique was used to integrate the variables from polarimetric and/or interferometric radar attributes and field inventory. Considering the terrain aspects where the tropical forest was located, the most significant variables for the biomass modeling were the Volumetric Scattering of Freeman-Durden target decomposition, Anisotropy, Relief Elevation, Slope, and the first and third helicity components of the Touzi model. For the Eucalyptus biomass model, the Interferometry Height and Canopy Scattering Index variables were significant. The statistical analysis based on field survey measures to validate each model, indicated a margin of error below 20% for the biomass estimations, showing the importance of SAR attributes for models of natural and planted forest stock density.*

Keywords: biomass modeling, forest inventory, radar data, tropical forest, Eucalyptus stand, remote sensing.

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Introduction

The current status of mapping and monitoring forest resources, at local, regional and global levels, has increased in importance as a tool for economic strategy. This is due to strong competition which predicts a rising market demand for wood products and especially for wood-based bioenergy. According to Koch [2010], there is also a growing need for information to improve the sustainability of our forests with regard to carbon flux magnitude, which is a significant area of scientific interest in terms of climate change.

Forest inventories assisted by remote sensing reap not only the benefit of incurring lower costs and obtaining results in less time than traditional methods, but also enable inventories to be conducted in large forest areas [Hou et al. 2011]. Some possibilities of and limitations to remote sensing data and methods (table 1), which can support mapping and forest inventory are listed by Gibbs et al. [2007]. The limitations to using remote sensing data for biomass mapping are related to data and appropriate method availability. The methods used today refer mainly to multispectral optical data sets and their digital classification methods, but often cannot fulfill the information requirements with regard to timeline and quality [Koch 2010]. This author mentioned that multi-sensor approaches based on polarimetric radar interferometry, fullwave laser, or hyperspectral data, have not yet been sufficiently developed to fill these gaps in information.

Within the range of sensor-products, this article focuses on how specifically remote sensing technology – RADAR – has been used in Brazil as a tool for the analysis of forest structure and its aboveground biomass. The physical principles of radar-interaction with the components of forest structure are complex, and determine the scattering mechanisms of the incident radiation that hits the forest components and returns to the RADAR sensor, the responses of which also depend on the imagery wavelength, polarization, and incidence angle of imagery [Koch 2010].

The methodological approach derived from the multi-polarimetric and/or interferometric Synthetic Aperture Radar – SAR data, enables detailed information on three-dimensional forest structure [Kasischke et al. 1997; Treuhaft et al. 2009] to be obtained. Indices based on ratios and normalized differences of multi-polarimetric data were developed and tested on tropical forests in Central America [Pope et al.1994]. These indices can be related to certain characteristics of vegetation cover, such as the biomass index [$BMI = (\sigma^o_{HH} + \sigma^o_{VV}) / 2$], the canopy structure index [$CSI = \sigma^o_{VV} / (\sigma^o_{VV} + \sigma^o_{HH})$], and the volume scattering index [$VSI = \sigma^o_{HV} / (\sigma^o_{HV} + BMI)$], where σ^o (sigma nought) refers to the scattering coefficient which describes the amount of backscattered power compared to that of the incident target; while HH, VV, HV polarizations are related to the state of polarization of the wave, that represent the electric field from the transmitting and receiving antenna (HH – for horizontal transmission and horizontal reception;

VV – for vertical transmission and vertical reception; and HV – for horizontal transmission and vertical reception).

Table 1. Benefits and limitations of remote sensing data to forest structure and biomass studies

Products	Description	Benefits	Limitations	Uncertainty
Optical remote sensors	– Use visible and infrared wavelengths to measure spectral indices and correlate to ground-based forest biomass measurements. Eg: Landsat, AVNIR/ALOS, HRV/SPOT, MODIS	– Satellite data routinely collected and available on regional and/or global scale – Regionally and/or globally consistent	– Limited ability to develop good models for tropical forests – Spectral indices saturate at relatively low C stocks – Can be technically demanding	High
Very high resolution optical remote sensors	– Use very high resolution images to measure tree height and crown area and allometry to estimate biomass stocks – Eg: 3D digital aerial imagery, IKONOS, QuickBIRD	– Reduce time and cost of collecting forest inventory data – Reasonable accuracy – Excellent ground verification for deforestation baseline	– Only cover small areas (10 000s ha) – Can be expensive and technically-demanding – No allometric relations based on crown area are available	Low to medium
Radar remote sensors	– Use microwave signal to measure forest vertical structure – Eg: ALOS/PALSAR-2, RADARSAT-2, COSMOSkyMed, TanDEM/TerraSAR-X	– Satellite data are generally free – Can be accurate for open or sparse primary forest and secondary succession	– Less accurate in complex canopies of mature tropical forests because signal saturates – Mountainous terrain also increases number of errors – Can be expensive and technically-demanding	Medium
Laser remote sensors	– LiDAR uses laser light to estimate forest height/vertical structure – Eg: Structure and biomass 3-D satellite system combines Vegetation canopy LiDAR (VCL) with horizontal imager	– Accurately estimates full spatial variability of forest carbon stocks – Potential for satellite-based system to estimate global forest carbon stocks	– Airborne-mounted sensors only option – Requires extensive field data for calibration – Can be expensive and technically-demanding	Low to medium

Source: Modified from Gibbs et al. [2007]

Neeff et al. [2005a] and Kugler et al. [2006] discuss the contribution of the interferometric mode to estimate biophysical parameters in forest areas. Some studies on radar applications conducted in Brazil to support the tasks of mapping, inventory and forest monitoring [Santos et al. 2003; Neeff et al. 2005b; Gama et al. 2010a; Treuhaft et al. 2010; Gonçalves et al. 2011; Saatchi et al. 2011; Li et al. 2012] explain the contributions of SAR attributes related to the structural complexity of primary and secondary tropical forests and also of reforested areas, when modeling of aboveground biomass and/or volume is needed. In this scenario, the present work aims to show the results derived from two scientific projects in Brazilian forest areas, as described below:

- to generate an estimating model of aboveground biomass of tropical forest, based on a combination of full-polarimetric attributes of the active microwave sensor PALSAR/ALOS (Phased Array type L-band Synthetic Aperture Radar/Advanced Land Observing Satellite), considering the influence of the geomorphometric aspects of terrain on the radar response;
- to generate an estimating model of aboveground biomass of *Eucalyptus* sp. stands, using a multivariate analysis for the associating coherent and incoherent polarimetric attributes in P-band, as well as the interferometric height derived from airborne SAR imagery with X- and P-bands.

Multi-attributes from PALSAR data for the modeling of aboveground biomass in Amazonian primary forest considering terrain aspects

The first study, was conducted in Tapajós National Forest – FNT (North East of Pará State, Brazil), at geographic coordinates S 2º42’24” – S 4º07’18” and W 54º52’37” – W 54º57’38”, a region dominated by Dense and Open Ombrophylous Forests and sections with legal and controlled timber exploitation activities. The local topography varies from flat (in the northern part of the area) to strongly undulating (in the southern zone). The predominant soil types in the area are Dystrophic Yellow Latosol and Red-Yellow Podzolic.

In this study, full polarimetric data from PALSAR/ALOS images (PLR format), in ascending mode, with a spatial resolution of 3.58 m in azimuth and 9.36 m in range, with an incidence angle of 24º were used. The geomorphometric attributes of the terrain (elevation and slope) for the area under investigation were derived from the Brazilian Geomorphometric Database – called Topodata – [Valeriano, Albuquerque 2010]. According to Valeriano, Rossetti [2012], the SRTM data, available from JPL/NASA [2001], was refined from 3 to 1 arc-second angle using a geostatistical technique, and the geomorphometric variables could be obtained using different neighborhood operations [Valeriano, Albuquerque 2010].

The geometric and radiometric calibrations of full-polarimetric PALSAR images were performed according to the methodology of Shimada et al. [2009]. These corrections were necessary to obtain the real values referring to the analysed images at $L_{HH,HV,VV,VH}$ -band. A scattering matrix (Sinclair matrix [S]) was generated, and then converted to a covariance matrix [C] and to a coherence matrix [T], applying a spatial averaging of 7 × 1 pixels. The spatial averaging permitted a conversion of the pixel spacing from approximately 3.58 m in azimuth by 9.36 m in slant range to 23 m in azimuth by 25 m in ground range. After this processing, the speckle noise was reduced using the polarimetric Refined Lee filter (5 × 5 window). The following incoherent attributes, which are based on information from the real part of each pixel, were considered: the backscatter coefficient ($\sigma°$), described by Woodhouse [2006]; the ratio of parallel polarization (Rp) and cross polarization (Rc), mentioned by Henderson, Lewis [1998]; and several indices formulated by Pope et al. [1994] in forest environments, known as the biomass index (BMI), the canopy structure index (CSI) and the volume scattering index (VSI).

These filtered polarimetric images, exploring the SAR phase-information, were also used to generate the coherent attributes: polarimetric coherence of HH-VV (γ) and phase difference of HH-VV ($\Delta\varphi$), described by Henderson, Lewis [1998]; the parameters resulting from the target decomposition by coherence matrix [T] according to Cloude, Pottier [1996] and Lee, Pottier [2009] known as entropy (H), anisotropy (A) and the mean alpha angle ($\bar{\alpha}$); the volume scattering components (Pv), double bounce (Pd) and surface (Ps), resulting from the decomposition matrix [C] [Freeman, Durden 1998]; and also, the magnitude (αs) and Touzi phase ($\Phi \alpha s$). Besides that, the orientation angle (ψ) and heliticity (τ_m), derived from two stages of the same former decomposition model were considered: (1) the Graves matrix [G]; (2) the Kennaugh-Huynen matrix, described in Touzi [2007] and Touzi et al. [2009], where a different procedure was used, with multilook 3x1 (azimuth x range).

The amplitude and phase information was generated in the reference system of the radar image (slant range) and the ground survey samples established for the forest inventory [Bispo et al. 2012] were projected for this system based on the process of inverse geocodification [Meier et al. 1993]. All the abovementioned polarimetric SAR attributes were extracted from ROIs – given Regions of Interest – which include a sufficient number of theme representative pixels, thus reducing statistical uncertainties and the influence of speckle noise. The field inventory was carried out based on DBH and height measurements of 4,448 trees (related to the 49 botanic families and 232 species) for 40 established independent plots (with a dimension of 2.500 m^2 each). Specific allometric equations of primary forest were used to calculate the aboveground biomass values of each sample according to the procedure in the study by Bispo [2012].

Considering the 40 plots duly georeferenced during the field survey, 30 of them were selected for generating the biomass model (10 plots situated on flat terrain, 10 on undulating and 10 on strongly undulating terrain), and the plots remaining were used to validate the best generated model (distributed also in the same geomorphometric types mentioned above).

To select the radar attributes (coherent and incoherent variables) for the regression model, the following were used as part of the methodological approach, during the interaction analysis of SAR and the field survey data (table 2): Mallow's Cp criterion (to assess the fit of a regression model which has been estimated using ordinary least squares), the R^2 (coefficient of determination) and R^2_{adj} (adjusted coefficient of determination) criteria (best subset), as well as some statistical procedures such as the presence of interaction effects (by bivariate interaction terms), the diagnosis of multi-collinearity (by calculus of Variance Inflation Factor – VIF) according to Stine [1995] and Neter et al. [1996], and the outliers (Cook´s distance) and residuals analysis [Neter et al. 1996].

Table 2. Statistical parameters derived from biomass model based on polarimetric and geomorphometric variables

Variable	β	SE	t	p	VIF
Constant	31.11	39.48	0.79	0.439	–
Pv	142.01	83.96	1.69	0.104	1.5
An	-598.3	161.7	-3.70	0.001	1.5
h	1.4635	0.1728	8.47	0.000	1.3
G	3.350	1.206	2.78	0.011	1.2
τ_m3	0.4288	0.2545	1.68	0.106	1.1
τ_m1	-9.478	3.723	-2.55	0.018	1.1

* R^2 = 79.4%; R^2 (adjusted) = 74.0%; R^2 (predict) = 55.29%; p = 0.000

The spatial arrangement of aboveground biomass density of tropical forest is very complex, where the topography is one of the principal aspects that affects this heterogeneity [Luckman 1998]. Thus, biomass density has a strong influence on radar response related to the scattering mechanisms. For this reason, it was also important to generate a model using geomorphometric variables (fig. 1). Therefore, based on the statistical criteria, the following final model ($R^2 = 0.74$ and $p = 0.0000$) was selected [Bispo 2012]:

$$AGB = 31.11 + 142.01\, Pv - 598.3\, An + 1.465\, h + 3.35\, G + 0.4288\, \tau\_m^3 - \\ - 9.478\, \tau\_m_1 \qquad (1)$$

where: AGB – the aerial aboveground biomass
Pv – the Freeman-Durden volumetric scattering
An – anisotropy
h – elevation
G – slope
τ_m_1 and τ_m_3 – helicity of the dominant (first) and lowest (third) scattering component generated by Touzi decomposition.

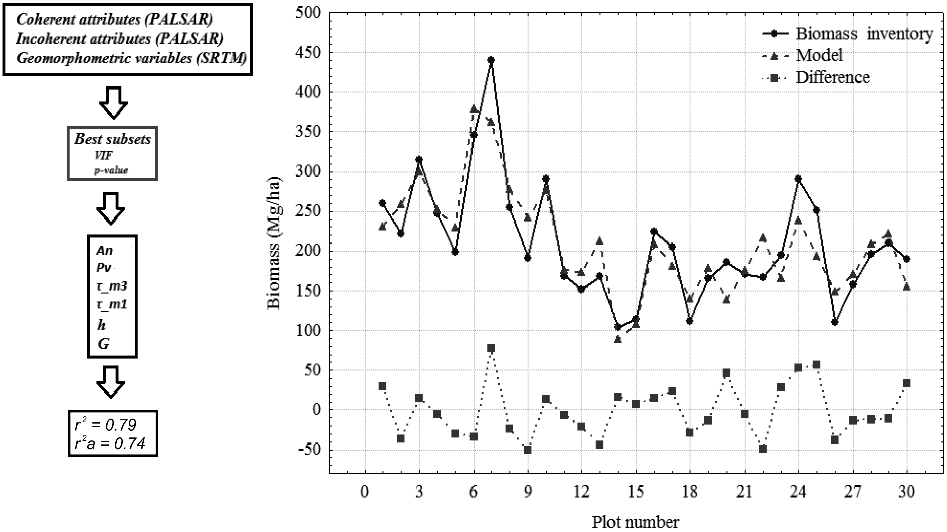


Fig. 1. Diagram showing the SAR attributes and geomorphometric variables used and the comparative behaviour of primary forest biomass from field survey and model in the Tapajós region

In this model, the anisotropy (*An*) showed a strong negative correlation with the biomass, indicating the presence of secondary scattering mechanisms, due especially to four strata composing the vertical structure of the Ombrophylous Forest in the Tapajós region. The τ_m_3 and *Pv* variables were positively correlated with the biomass, due to the number of trees spatially distributed at several forest strata. This forest arrangement is considered a cloud of randomly oriented dipoles, showing a good adherence to the theoretical polarimetric signature model proposed by Zebker, Norikane [1987]. In additional to the high biomass content, this arrangement with its high quantity of randomly-distributed elements, also controlled the SAR backscatter within the image resolution cell.

During the field inventory, the total observed biomass was 210.02 t/ha. with a standard deviation of ±74.31 t/ha. The configuration of biomass values from the model was compared with the biomass estimated in the field survey, using 10 independent plots (AGB mean value of 210.68 ± 40.54 $\mathrm{Mg\cdot ha^{-1}}$). The RMSE values were approximately 42.96 $\mathrm{Mg\cdot ha^{-1}}$, whose validation, estimated by the model, showed an error of 20% compared to the mean observed aboveground biomass on the Tapajós site.

Polarimetric and interferometric airborne SAR data for the aboveground biomass estimation of *Eucalyptus* sp.

In Brazil, a significant amount of carbon dioxide (1.3 billion tons) and other greenhouse gases (GHGs) are sequestered from the atmosphere by *Eucalyptus* and pine forest plantations, contributing to the mitigation of climate change effects [Folha da Bracelpa 2013].

Nowadays, there are approximately 6.7 million hectares occupied by homogeneous planted forests in Brazil, with a pulp production of 14 tons per year, thus generating 9.8 tons of paper per year.. This activity resulted in a trade balance of US$ 4.7 billion in 2012 [Brasil Econômico 2013]. In addition, there is a strong charcoal production. The horizontal expansion and value increase of the forest-based sector have encouraged the improvement of mechanisms for inventory and the monitoring of forest farms with advanced remote sensing tools, especially with high resolution optical images, LiDAR [Zonete et al. 2010; Oliveira et al. 2012; Macedo et al. 2013]and also radar data [Gama et al. 2010a]. Such issues are of interest to reforestation companies seeking to minimize their costs, as well as to improve control and management efficiency. Moreover, remote sensing techniques improve the accuracy of forest measurements when compared with traditional field inventory, allowing a synoptic view of the forest.

Within this context, a second study was carried out in the Paraíba River Valley (W 45° 23’ to 45° 25’and S 22° 54’ to 22° 55’), São Paulo State, using airborne OrbiSAR system to provide the radar data from a reforested area with *Eucalyptus* sp. (6 year old stands ~, spaced 3 m × 2 m and tree height varying between 14 to 23 m).

The airborne data acquisitions were carried out in X_{HH}-band (1 m resolution) and in fully polarimetric P-band (range and azimuth resolution of 2 m), both with a 45° boresight angle. The mapping flights were crossed to minimize the shadowing effect, and so the image regions which lacked information due to shadows were filled in by mosaic techniques. X-band interferometry was carried out in one pass with 2.77 m of baseline, while for the P-band interferometry two passes were necessary with 50 m of baseline. X-band coherence, DEM (Digital Elevation Model) and complex images were generated in HH polarization. P band data, as interferometric coherence, DEM and complex images were obtained in four polarizations.

These microwave data (X- and P-bands) were radiometrically calibrated using corner reflectors. The antenna pattern correction was performed using a homogeneous target area. The polarimetric calibration was also performed to minimize the distortions imposed by the SAR system in the scattering matrix (cross-talk and channel imbalance), using the method proposed by Quegan [1994].

The *Eucalyptus* aboveground biomass model was estimated by linear regression modeling between the field inventory data and the interferometric and polarimetric airborne SAR data. The field inventory data was collected based on the measurement of DBH and height values of 80 trees for each one of the established 23 plots of 400 m^2. The absence of trees in the forest stand was also studied, because it caused a reduction of biomass values in each plot. During the field survey, the biomass of the stands was obtained by a destructive method. One representative tree from each plot was selected, the DBH value of which was similar to the average found for all individuals of each sample. Then, these selected trees were cut-down and weighed to represent the whole stand. Simultaneously, some topographic profiles were carried out using an infrared Total Station (Topcon, GTS-701 model with 3 arc-second angle accuracy) for the analysis of P_{HH}, P_{HV}, P_{VV} interferometric DEM quality (Digital Elevation Model), which showed the lowest standard deviation of 2 m [Gama et al. 2010b]. On the other hand, the comparison of the sum of inventoried tree heights with these topographic ground measurements, and with X band DEM heights, indicated a standard deviation of approx. 3.4 m.

To select the SAR coherent and incoherent variables (fig. 2a) for the regression model, Stepwise, Cp, R^2 and R^2_a criteria were used, as well as Cook's distance to find the outlier cases. Levene's method was used to verify the homoscedastic behavior of regression residues. Based on this approach, the variables $Hint^2$ (Hint – difference between interferometric values in X- and P-bands) and CSI (measure of the relative importance of vertical versus horizontal structure in the forest cover) presented a linear behavior, the final model of which is:

$$AGB = -114.505 + 0.137\, H_{int}^{2} + 316.058\, CSI \tag{2}$$

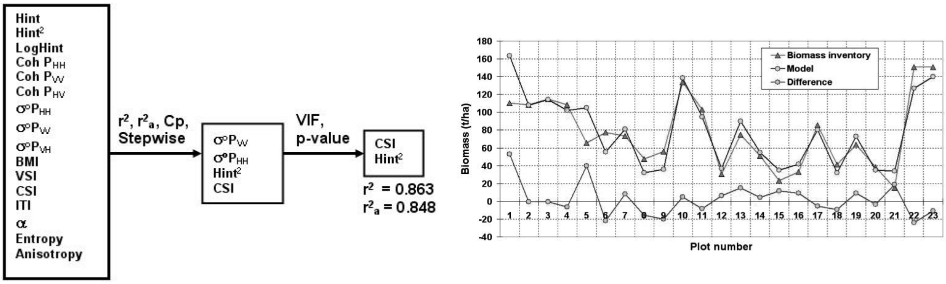
where: AGB – the aerial aboveground biomass
H_{int} – interferometric height obtained from the difference between interferometric digital elevation models in X-and P-bands
CSI – canopy structure index from Pope's ratio, which represents the microwave interaction with the vegetation canopy.

Table 3 presents the statistical values derived from this aboveground biomass model. The AGB model obtained a determination coefficient of 0.863, with one outlier case related to plot 1. The CSI variable brought some radiometry contribution of $\sigma°P_{VV}$ and $\sigma°P_{HH}$, therefore the radiometry contributed to the model due to fact the interaction of the radar beam with the vertical and horizontal stand elements (branches, leaves, and stem) represented by the CSI index. The squared Hint ($Hint^2$) variable strongly contributed to the biomass model too, since *Eucalyptus* biomass has a second order relationship with its height.

Table 3. Statistical data from the regression biomass model of *Eucalyptus* stands

Variables	β	p-value	MSE	PRESS	R^2	$R^2_{adjusted}$
Intercept	-114.505	4.89%	245.26	6187.43	86.29%	84.84%
$Hint^2$	0.137	0.013%				
CSI	316.058	2.18%				

The aboveground biomass model is very similar to the inventory data (23 plots) in the Eucalyptus stand (fig. 2b). The biomass variations of all the plots obtained during the ground survey were related to the different local site index where the forest stands were located and also to the particular genetic differences (seminal and clones) of these plantations.



(a) (b)

Source: adapted from Gama et al. [2010a]

Fig. 2. Diagram of SAR attributes tested to generate the model (a); and comparative behaviour of aboveground biomass modeling of *Eucalyptus* sp. stands (b)

The criteria PRESS (Predicted Residual Sum of Squares) and SSE (Sum of Squared Errors) were used to validate the model (table 3). This allowed the use of MSE (Mean Squared Errors) to predict the errors [Neter et al. 1996; Rencher, Schaalje 2008]. The MSE for the biomass regression model presented a value of 245.26, which meant that this biomass model had a prediction error of 10.38% when compared with the minimum stand biomass.

Conclusions

Currently, polarimetry and interferometry research concepts largely focus on tropical regions, not only to map deforestation and degradation caused by timber exploitation or by forest fire actions, but also to be used as input for biomass calculations. These SAR techniques can be directed to improve biomass estimations, which have recently been methodologically developed in Brazil, by Gonçalves et al. [2011], Saatchi et al. [2011]; Sambatti et al. [2012], Santos et al. [2013] among others.

Based on the two results presented in this paper the following conclusions have been reached:

- Relief elevation and slope orientation attributes are innovative variables in the calculation of aboveground biomass of tropical primary forest, which, associated with the SAR attributes from the volumetric scattering of Freeman-Durden target decomposition, anisotropy, and the first and third helicity components of the Touzi model, improve the consistency of this estimation prediction using L-band data.
- The aboveground biomass modeling of *Eucalyptus* stands, when incorporating interferometric height and incoherent attributes (Canopy Structure Index

from the Pope equation), provide a higher degree of accuracy in the estimation process. The interferometric SAR attributes have a strong relationship with the *Eucalyptus* biomass content, because reforested area is clear in the understory strata, and the species under study has a small canopy despite its great height.

– In both the cases mentioned above, according to a set of independent data from the field inventory used for model validation, the results showed an error margin below 20% for estimates of aboveground biomass. This demonstrates the potential of SAR technology tools for the biomass modeling of natural and planted forest stock density, within an acceptable accuracy, and for optimized surveys of large areas, compared to traditional inventory. The methodology presented here can be applied to support management and monitoring tasks for the production and control of the Brazilian forest landscape.

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Acknowledgements

The authors would like to acknowledge CNPq and CAPES for the research grants, and Nobrecel Celulose e Papel S.A., Diâmetro Biometria e Inventário Florestal, ORBISAT da Amazônia S.A., ICMBio/MMA, and LBA Office (Santarém-PA) for the logistic support.