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Contribution of polarimetric SAR attributes for modeling of the tropical forest biomass affected by fire.

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Abstract. This study presents the capability of full polarimetric PALSAR ALOS attributes to improve the aboveground biomass (AGB) modeling of forests affected by fires in the Brazilian Amazon (State of Roraima). To perform this study, we carried out multivariate regression, using coherent and incoherent SAR attributes and AGB values estimated through biophysical parameters obtained during the forest inventory. The PALSAR data were calibrated both radiometrically and geometrically to extract the polarimetric informations. In summary the results were: (a) considering the polarimetric signatures, we observed a higher scattering contribution of VV polarization in lightly burned forests, whereas there was a dominance of HH polarization scattering in the areas with the interannual recurrence of biomass burning; (b) the most significant variables for this tropical forest biomass modeling were: the anisotropy **(A)** derived from the eigenvectors and eigenvalues of Cloude & Pottier target decomposition; the orientation angle **(ψ_2)** of second component of Touzi decomposition; the *double-bounce* scattering component **(P_d)** of Freeman & Durden decomposition; and also, the Volumetric Scattering Index **(VSI)** of Pope model. In order to validate this model using PALSAR images, a cross-validation method (leave-one-out) was performed, which indicated a prediction average error of 23% to estimate the stock density of forests affected by fire actions, where the AGB levels were reduced up to 60%. This study confirm that L-band PALSAR data can be applied to quantify and monitoring the carbon stocks in the tropical forest affected by fire, with an adequate accuracy, similar to that presented by traditional forest inventories.

Keywords. Biomass modeling, forest fire, SAR data, tropical forest, monitoring.

1. Introduction

The availability of updated information on the geographical scope and extent of burned areas is critical to evaluate losses as well as socio-economic and ecological effects, allowing the reorientation of policies on land occupation. This information are also useful for the subsidization of atmospheric and climate impacts models (particulate emissions and transportation) due to burning of plant biomass contained in this type of anthropization [1], [2] and [3].

Images from the NOAA/AVHRR satellite series and the AQUA and TERRA/MODIS platforms, as well as MERIS (Medium Resolution Imaging Spectrometer), have long been used for the detection of forest fires and the positioning of these areas affected by burning, as cited as in [4] and [5].

Studies of emissions from biomass burning in South America [3] include the research of [6] in the cerrado (savanna) of Brazil central region and the Amazon rainforest. These studies show estimates of aboveground biomass (kg.m-2) and combustion factor (fraction of biomass actually burned) ranging from 0.71 and 100% until 1.00 and 84% according to the cerrado facies, from 12.14 and 43% for secondary forest and from 29.24 and 52% for primary forests. Biomass estimates for various Amazonian sites vary widely, constituting one of the main sources of uncertainty in the estimates of carbon fluxes associated with land use change.

In this context, considering that the area of the present study is located in the northern part of Brazilian Amazon, it is interesting to read the papers [7] and [8], who analyze the effects of floristic-structural degradation due to the fire history of forest biomass. These two works support the objective of the present study, which makes use of full polarimetric data from the PALSAR radar to improve the aboveground biomass (AGB) modeling of forests affected by fires.

The use of radar data in recent studies of tropical forests has demonstrated several applications: the characterization of tropical forest typology [9] and [10]; the analysis of polarimetric responses of forest targets [11]; and the use of biophysical parameters for volumetric and biomass modeling [12], [13], [14] and [15]. Specific studies employed a fusion of optical and radar data for detection and spatial assessment of forests affected by fires in the tropics [16] and [17]. However, it is important to note that this present work is considered innovative in the Brazilian Amazon as it deals with polarimetric attributes for the characterization and modeling of biomass in forest areas affected by historical incidence of fire. This line of research with radar data is important in supporting estimates of carbon sequestration and degradation of tropical landscape, as quoted in [18].

2. Material and Methods

The study area is located in State of state, in the extreme north of the Brazilian Amazon (W 61° 03' – W 61° 46' and N 02° 09' – N 02° 47'). This area was indicated as the center point of the great fire of Roraima in 1998, whose uncontrolled occurrence originated from the use of fire as a traditional practice of land conversion and clearing, and, under the influence of "El Niño" [19], reached forests and savannas. The climate of this region is rainy tropical with a dry season from December to March. The forest mosaic is composed of Tropical Rain Forest (Dense and Open) and Seasonal Forest in a transition zone with savannas.

Two PALSAR ALOS images (L-band) in the complex format (SLC), full polarimetric mode and ascending orbit, were used. The acquisition dates of these images corresponded to April14th, 2009 and May 30th, 2009, with angles of incidence of 23.96° and 25.78° respectively, and with resolution in slant x azimuth of ~ 9.4 m x 3.6 m.

Polarimetric and radiometric calibrations and a resampling procedure (*multi-look*) were initially performed on these images, followed by the application of a modified Lee filter with a window size of 5x5 pixels. The complex scattering matrix, comprising amplitude and phase values, possesses different polarimetric characteristics described by a set of radar attributes that express the behavior specific to each forest target. This allowed the configuration of the polarimetric signatures [20] of each forest class for a given region of interest (ROI) – a sample area that includes a sufficient number of representative pixels of theme, reducing the statistical uncertainties and the influence of the speckle noise – previously defined in the radar images, with consideration of the frequency of fire over the years. It also allowed for the extraction from the complex matrix of the coherent and incoherent attributes that would subsequently be related to the values of aboveground biomass.

The following incoherent attributes, which are based on information from the real part of each pixel, were considered: backscatter coefficient (σ°), described by [21]; the ratio of parallel polarization (Rp) and cross polarization (Rc), mentioned by [22]; the indices, formulated by [23], referred to as a biomass index (BMI), canopy structure index (CSI) and volume scattering index (VSI).

The coherent attributes, which take advantage of SAR phase information, were evaluated: polarimetric coherence of HH-VV (γ) and phase difference of HH-VV ($\Delta\varphi$), described by [22]; parameters resulting from the decomposition [24] by coherence matrix [T] called as entropy (H), anisotropy (A) and the mean alpha angle(□ $\Delta\overline{\alpha}$); the volume scattering components (*Pv*), double bounce (Pd) and surface (Ps), resulting from the decomposition matrix [C] from [25]; the magnitude

(αs) and Touzi phase ($\Phi\alpha s$), beside that the orientation angle (ψ) and heliticity (τ_m), also derived from the same former decomposition [26] were analyzed.

All these attributes were extracted in ROIs representing each thematic class, properly georeferenced and inventoried in the field survey for measure the biophysical parameters that served to model the biomass through generic [27] and specific [28] allometric equations. A detailed description of this inventory procedure can be found in [7] and [8].

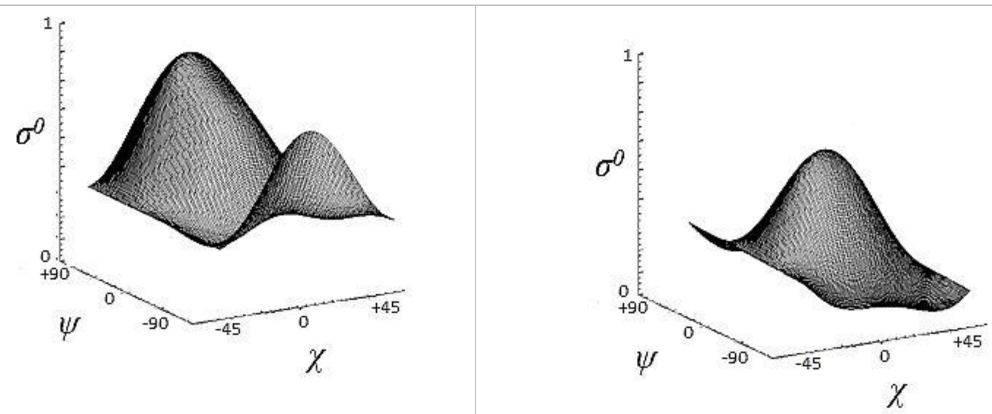
Multiple regression analysis was employed to assess the sensitivity of PALSAR polarimetric attributes to variations in forest biomass. This generated model was adjusted through the method of Ordinary Least Squares (OLS). The selection of explanatory variables was carried out using the *Stepwise* package, with values of significance $p < 0.15$ and permanence $p < 0.05$ as criteria for entering variables into the model. The performance analysis of this model used the R^2 and $R^2_{adjusted}$, RMSE values, as well as some statistical procedures such as the diagnosis of multi-colinearity (by calculus of Variance Inflation Factor - VIF), analysis of outliers (Cook´s distance) and residuals. The last phase of the methodological procedure was validation of the generated model using the cross-validation method "*leave-one-out*", as described in [29].

3. Results

For each representative ROI from the 5 thematic classes (Table 1) in the PALSAR images, an exploratory analysis was conducted on their respective cross sections (σ^0), which is represented in a three-dimensional graph as a function of all combinations of orientation angles (ψ) and ellipticity (χ) relating to the ellipse of polarization. To illustrate this exploratory phase of characterization of forests affected by fire, two examples from their polarimetric signatures are given (Figure 1).

Table 1. Classes of fire disturbance, year(s) of fire occurrence(s), sample number (n) and total area (State of Roraima).

Fire disturbance classes	**Year(s) of fire occurrence(s)**	**N**	**Area (ha)**
Unburned forest	-	6	1.5
Once lightly burned forest	1998	4	1
Once heavily burned forest	1998	8	2
Twice-burned forest	1998, 2003	11	2.75
Thrice-burned forest	1998, 2003, 2007	10	2.5
Total	-	39	9.75



(a) (AGB= 132.2 Mg.ha^{-1})   (b) (AGB= 75.2 Mg.ha^{-1})

Figure 1. Polarization responses from PALSAR data over the forests affected once lightly burned (a) and thrice burned (b) in State of Roraima.

In general, the polarimetric signature of forest class "once lightly burned" in the L-band, has a similar configuration as the response from a forest not affected by the fire. In this three-dimensional graph, peaks of backscatter (σ^0) can be seen in the vertical polarization ($\psi \approx \pm 90°$) with relatively less contribution (σ^0) to horizontal polarization ($\psi \approx 0°$). There is some similarity with the canonical response of an oriented cylinder [30], however, indicating a relatively larger contribution from small branches of forest structure influencing the response [29]. For the forest class "thrice burned ", the polarimetric response is associated with dipole targets that can, in this case, be represented by fallen logs arranged horizontally on the forest surface, with greater openness of the canopy and a more simple vertical structure in terms of layers.

During the step of biomass modeling based on SAR attributes, 39 plots encompassing the total area of 9.75 ha (Table1) were selected for forest inventory. Primary forests not affected by fire had mean values of 188±78 Mg.ha^{-1}, similar to those obtained by [31]. Once lightly burned forest with average biomass of 162.9±57 Mg.ha^{-1} did not differ significantly from those of primary forests. In turn, forests once heavily burned, twice and three times had values of 118.7±52 Mg.ha^{-1}, 108.1±48 Mg.ha^{-1} and 70.1±32 Mg.ha^{-1}, as cited by [7]. The resilience of the forest in terms of biomass depends on the history of fire, including the frequency and severity, as well as the conditions of site index and the forest matrix in which the burned area was inserted.

Based on the statistical criteria the final model (with $R^2 = 0.79$ and $R^2_{aj.} = 0.76$; RMSE = 32.1 Mg.ha^{-1}, that represents an error of ~27.8% in relation to the biomass mean values, according [29] was selected:

$$AGB = 272.8 + 0.4 * \boldsymbol{\psi_2} - 1146.1 * \mathbf{A} + 565.2 * \mathbf{P_d} - 213.3 * \mathbf{VSI}$$

Onde:
AGB = aboveground biomass in Mg.ha^{-1};
$\boldsymbol{\psi_2}$= orientation angle of second component derived from Touzi decomposition model;
A = anisotropy value from the autovectors and autovalues of the Cloude & Pottier decomposition;
$\boldsymbol{P_d}$ = *double-bounce* scattering component derived from Freeman and Durden decomposition;
VSI = volumetric index of Pope.

All these variables have *p*-values less than 0.05. Through analysis of the predicted values relative to those observed, no saturation point signal was identified (Figure 2) using L-band attributes.

As the resulting RMSE value represents an average error of ~ 27.8%, biomass classes were stratified by interval, showing that in this model the estimation accuracy was lower for smaller values of AGB. This fact is contrary to reports in the literature (studies in primary forests), where accuracy decreases with increasing values of biomass, which is often associated with saturation of the signal.

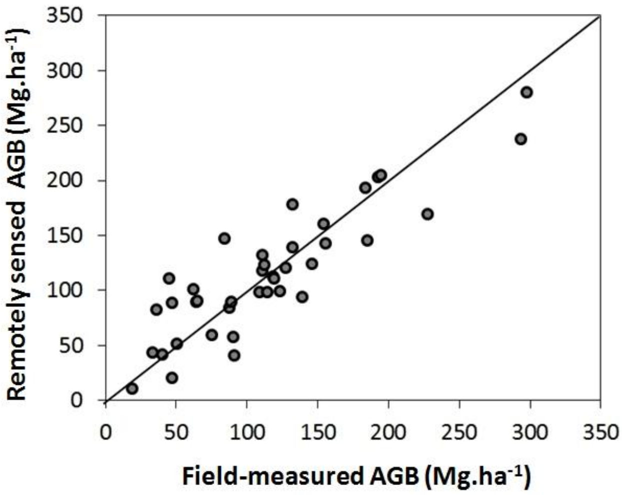


Figure 2. Scatterplot of field-measured biomass for the plots established during the forest inventory (x axis) versus the remotely sensed biomass (y axis) as calculated from the best model. Source: adapted from [29].

Through the *leave-one-out* method for cross-validation of this model in the estimate of aboveground biomass, found the mean absolute error value equal to 26.6 $Mg.ha^{-1}$(prediction average error of 23%).The prediction errors were also smaller in this procedure as the higher biomass values observed can be attributed to the behavior of the anisotropy variable, noisier in the PALSAR images of those forested areas most affected by the fire. Thus, adequate sensitivity of the polarimetric data in L-band to variations in biomass content derived from the action of fire can be verified.

4. Conclusions

Through the polarimetric responses and the scattering mechanisms in the interaction of radar signal versus forest targets, one can verify adequate sensitivity of L-band data to variations in biomass content derived from the action of fire.

The results of this scientific study shows the target decomposition attribute of Touzi (**ψ_2**) is an innovative variable for the estimative of aboveground biomass of tropical forests affected by fires, associated with the effect of the anisotropy variable, and statistically very significant in the composition model. This study corroborates the hypothesis that L-band SAR data can be used to quantify and monitor the biomass of forests affected by fires with adequate accuracy compared to that obtained by traditional forest inventories

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