Tropical forest biomass and its relationship with P-band SAR data

Biomassa de floresta tropical e sua relação com dados de radar de abertura sintética (SAR) em banda P

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ABSTRACT

The objective of this research is to show the potential of P-band polarimetric SAR images to define the space of attributes of primary and regenerating forest and also to estimate aerial biomass of such formations. The approach used was the analysis of the relation between backscatter and biomass data estimated by four specific allometric equations. The Bivariate Intensities HH-HV image was segmented and the mean s° of each segment was converted into biomass by the best fit function (the heat capacity model) and following that the biomass was mapped. As a conclusion, the best allometric equations for primary and secondary forest biomass estimation were defined, considering the different polarizations of P-band SAR data. The methodology used in this treatment of P-band data might improve the regional monitoring of Amazonian land cover change, a process whose speed was accelerated as a result of human action in the Amazon during the last two decades.

Keywords: biomass, radar, monitoring, tropical forest, vegetation mapping, remote sensing.

RESUMO

O objetivo desse trabalho é apresentar a potencialidade de imagens polarimétricos de radar de abertura sintética em banda P como suporte na definição do espaço de atributos de florestas primária e secundária e também na estimativa de biomassa aérea de tais formações. No procedimento metodológico utilizado foi feita a análise da relação entre valores de retroespalhamento e aqueles de biomassa estimada por meio de quatro equações alométricas específicas. Uma imagem-radar de intensidade bivariada HH-HV foi segmentada e o valor médio de retroespalhamento (s °) de cada segmento foi convertido em biomassa fazendo uso da melhor função de regressão ajustada (no caso, "*heat model capacity*"), gerando assim, posteriormente, uma mapa de biomassa das feições presentes na área estudada. Como conclusão, obteve-se a sinalização das equações que melhor expressavam a estimativa da floresta primária e das sucessões secundárias, considerando as distintas polarizações da banda P. A metodologia utilizada no tratamento dos dados-radar em banda P pode implementar ainda mais o processo de monitoramento das transformações de cobertura da terra em setores da Amazônia, cuja dinâmica de mudanças tem sido acelerada como resultante das variadas práticas humanas de ocupação, principalmente nas duas últimas décadas.

Palavras-chave: bio massa, radar, monitoramento, floresta tropical, mapeamento da vegetação, sensoriamento remoto.

1. INTRODUCTION

With the advance of remote sensing technology, SAR data are available to supply and/or to complement the information provided by optical sensors to assessment and monitoring of tropical rain forest environment (van der Sanden & Hoekman, 1999). For the estimate of biophysical variables of vegetation, SAR data present inherent limitations related to the frequency used. In general, the microwave scattering at P-band has the advantage of being more sensitive to the standing biomass variations than X, C and L-bands, due to its longer wavelength which penetrates the forest crown, getting consequently more interaction with the structural aspects of tree boles and larges branches (Le Toan *et al*., 1992; Hoekman & Quiñones, 2000), as well as the ground surface. Kasischke *et al*. (1997) while describing the use of C-, L- and P-band data for ecological applications, concluded that imaging radars have the capability of monitoring variations in biomass of forested ecosystems, but that this capacity is not consistent for different forest typologies; at these frequencies, the smaller woody stems and the foliage act mainly as attenuators.

Within this context, a scientific experiment performed in the Tapajós region, aimed to provide airborne SAR data at P-band and also X-band (whose frequency of radar were studied for the analysis of spatial forest features by NEEFF *et al*., 2005) over Brazilian tropical rainforest, using a system developed by the German AeroSensing RadarSysteme GmbH Company.

The objectives of this study were:

- to assess the potential of P-band polarimetric SAR data to map forest biomass .
- to investigate the biomass/backscatter relationship according to different allometric equations.

To achieve these objectives, intensity P-band images were segmented and the backscatter coefficient (s°) mean value of each resulting segment was converted into biomass by the equation that best defined the biomass and backscatter relationship.

2. MATERIALS AND METHODS

The airborne SAR images were obtained by a system that acquires P-band (fully polarimetric), whose technical properties were: wavelength 72 cm, middle frequency 415 MHz, depression angle 45° (37-51°) , range resolution 1.5m, azimuth resolution 0.7m for 1 look slant range image.

The radar tracks were radiometrically corrected according to the antenna pattern using a function based on homogeneous extended areas. The polarimetric calibration was done for each polarization (slant range mode), based on the 8 corner reflectors placed in the field along the flight strips using differential GPS measurement. The backscatter coefficient (s°), herein called backscatter, was estimated by the procedure adopted by SANTOS *et al*. (2003).

2.1. Study area and field survey

The study area is located at the lower Tapajós River region (Pará State, Brazil), between W 54° 53' to 55° 06' and S 3° 03' to 3° 12', along highway BR-167 that links Cuiabá to Santarém. The yearly rainfall varies between 1,750 mm and 2,000 mm. The distrofic yellow latossol (oxisol) soil type predominates in two textural classes: clay and medium clay. These are normally deep soils, found over hilly to strong hilly terrain, covered by dense forest of lowlands and sub-montane. Human occupation is related mostly to subsistence farming (rice, cassava, maize, beans, pepper) and extensive cattle raising.

During the field survey, DBH (diameter at breast height) > 5 cm and also total height were measured for trees in mature forest and secondary succession plots of 2,500m^2 and 1,000m^2 respectively. The regenerating forest areas were inventoried to represent three stages of succession: initial, intermediate and advanced. It was considered the forest stratification that differs according to (i) the age of the natural regrowth, (ii) forest structural characteristics and of (iii) floristic composition found in such facies. Inside plots a total of 3,210 trees were measured in both vegetal cover.

2.2. Correlation analysis

It was investigated the correlation of backscatter with the following variables estimated for the forest plots: (a) average tree height; (b) percentage of trees with height<10 m; (c) percentage of trees with height>10 m; (d) percentage of trees with 5 cm<DBH<15 cm; (e) percentage of trees with 15 cm<DBH<30 cm, (f) percentage of trees with DBH>30 cm and (g) forest biomass.

2.3. Biomass estimates

The forest plots biomass was estimated using allometric equations, based on dendrometric variables such as DBH and/or height, measured during the field survey. The following allometric equations were used for mature forest:

$$\text{biomass} = 0.044 * (\text{DBH}^2 * \text{height})^{0.9719} \quad (1)$$

$$\ln(\text{biomass}) = -0.370 + 0.333 \ln(\text{DBH}) + 0.933 [\ln(\text{DBH})]^2 - 0.122 [\ln(\text{DBH})]^3 \quad (2)$$

according to Brown *et al*. (1989) and Chambers *et al*. (2001) respectively. For the biomass estimate of secondary forest were applied:

$$\ln(\text{biomass}) = -1.9968 + 2.1428 \ln(\text{DBH}) \quad (3)$$

$$\ln(\text{biomass}) = -2.17 + 1.02 \ln(\text{DBH})^2 + 0.39 \ln \text{height} \quad (4)$$

according to Nelson *et al*. (1999) and Uhl *et al*. (1988) respectively.

The combination of some of these allometric equations considering mature and regenerating forest plots allowed to verify, through regression models, the equation defining the relationship between above ground biomass and P-band backscatter in different polarizations. Based on the equation that best fitted the biomass and backscatter relationship (defined by the Curve Expert 1.3 Program), the biomass was mapped following the steps reported below.

2.4. P-band image processing

After a series of P-band data processing to map different land use/land cover types in Tapajós test-site, we concluded that a Bivariate Intensity HH-HV image, according to the formulation of LEE *et al*.(1995), presented an adequate performance ($\hat{k}$ = 0,6791; $\sigma^2 = 4.32\text{x}10^{-6}$). In Bivariate Intensitiy HH-HV images, it was possible to discriminate mature forest, old regenerating forest, intermediate/new regenerating forest, floodplains and agriculture/pasture.

Based on this conclusion, the thematic limits of this classified image were used as regions and superimposed in the intensity P_{HH} image. These regions were spatially eroded (filter of 3 x 3 pixels) to minimize error on border definitions. Following this, the regions which have less than 50 pixels were deleted. The resultant segmented image was applied as a mask over a Gamma filtered image (windows of 8 x 8 pixels) to extract the mean backscattter value of each region. This extraction was conducted by the estimation of a trimmed intensity, where 5% of the upper and lower intensity values were discarded. Both procedures, deletion of regions and trimming of intensity values, helped on the reduction of measurements variance. In those regions with less than 50 pixels, the biomass was estimated by averaging values according to the thematic targets that were previously defined in the classified Bivariate Intensity image.

This study presents the results of mapping biomass from the P_{HH} backscatter only, because in the Tapajós test-site this polarization had a better performance to define the relation between biomass and backscatter (SANTOS *et al*., 2003)

3. RESULTS

The average value of biomass in mature forest plots was 242 ton/ha, with an average of 900 trees/ha (DBH>5 cm). Secondary succession types presented a higher concentration of individuals in the lower stratum (H<10m), with mean biomass of 41 ton/ha and 1,400 trees/ha. The lower biomass in regenerating forest plots is related to the different age of regrowth stage and also to the intensity of previous land uses.

Comparing the biomass estimates for mature forest plots, the biomass estimated by the allometric equation by (2) presented an increase of about 20% if compared to the biomass estimated by the equation by (1) (Fig. 1a). For secondary succession the biomass estimated by the allometric equation from (3), presented an increase if compared to biomass estimated by the equation by (4). The Fig.1b illustrates the correlation values between the physiognomic-structural variables of the vegetation types and the polarimetric P-band SAR data. When analyzing the physiognomic-structural variables, those trees with DBH above 15 cm presented a significant influence on the P-band response at HH and HV polarization. The correlation of tree height with SAR data, independently of class intervals, was moderate.

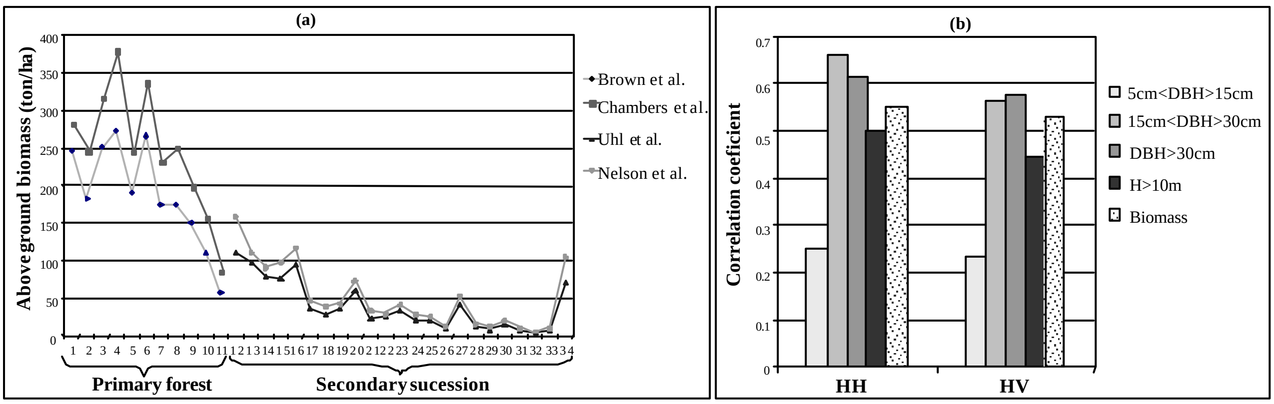

Fig. 1- Diagrams showing (a) the average values of biomass derived from specific allometric equations for each plot of primary forest and regrowth areas at Tapajós region; and (b) correlation values among biometric features of vegetation typologies and P- backscatter data at different polarizations

The biomass data generated by the combination of allometric equations by (2) for primary forest and by (4) for secondary forest, presented a higher relationship with backscatter in P_{HH} images. Such combination of allometric models produced different results when HV polarization was used. Biomass estimates from Browns' (mature forest) and Nelsons' equation (secondary succession) presented fit better at this relationship with HV datasets. This indicated that, at the biomass study of primary forest with cross polarized data (HV), the tree height component should compose the allometric estimate equation of this parameter, to have an adequate fitting of this model. The same does not apply to HH polarization, where the simple use of DBH to estimate biomass is enough to fit field survey and SAR data.

In the case of secondary succession, an inverse process than that of primary forest occurs. Data seemed to indicate that at the P-band cross-polarization (HV) there was less variations in tree height (more homogeneous canopy) and that DBH was sufficient to model the biomass. However for polarization HH, the simple change of regrowth tree height seems to have some importance as a complementary indicator of biomass modeling. Therefore, to model biomass of secondary succession, information about tree height should be included when using co-polarized SAR data.

Based on the best fitted regression model (Fig. 2) namely: **[y = -6.386849 + 0.006265x + (-137.02487/x^2)]**, obtained using Chambers and Uhl equations, the biomass was mapped as a function of backscatter from P_{HH} images (Fig. 3). The legend of this map is biomass range which allowed the characterization and verification of the spatial distribution of vegetation cover in the study area. Associated to this type of information obtained from P-band images, it is very important to collect information, during field surveys, about the structural and floristic aspects of the vegetation types, whose components can influence the radiometric behavior of the radar signal.

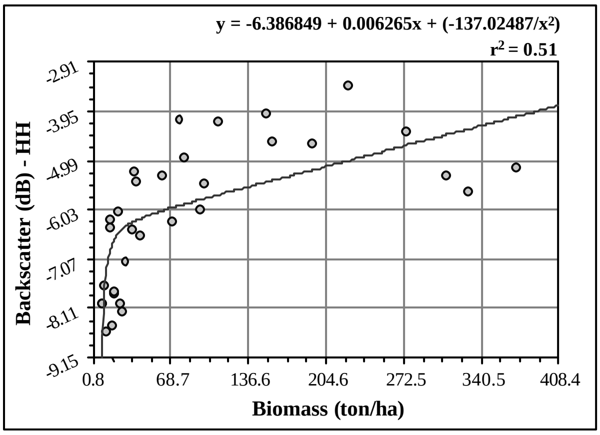

Fig. 2 - Response of P_{HH}-backscatter plotted against above ground biomass values.

The P-band polarimetric SAR data showed some potential when mapping tropical mature and regenerating forest biomass. However, the relationship between forest biomass and the P-band SAR data saturated at intermediate levels of biomass. This saturation point did not allow the biomass estimation at levels of tropical mature forest biomass (SANTOS *et al.*, 2003), limiting the analysis conducted here. However, the heat capacity model, used to relate P-band backscatter (HH polarization) and biomass (r^2 = 0.51), extended the range of biomass estimated with P-band SAR data.

New approaches to tropical forest inventory are being sought. NEEFF *et al.*, (2003) are used P_{HH} backscatter and interferometric height measures of forest cover (derived from X_{HH} and P_{HH} backscatter), allowing biomass estimation from 5 ton/ha (initial regrowth) up to 350 ton/ha (mature forest), with r^2 >0.90. Polarimetric radar interferometry is much more sensitive to the distribution of oriented targets in a vegetated land surface than either polarimetry or interferometry alone (TREUHAFT & CLOUDE, 1999). Thus, these measurements are now being also favorably considered for forest inventory and monitoring. A major problem in forest biomass retrieval from SAR data is the contamination of radar measurement by a number of other environmental variables, where the multifrequency and multipolarization datasets have been mainly considered to mitigate these effects (DEL FRATE, 2004).

4. CONCLUSIONS

The heat capacity model had a moderate performance (r^2 = 0.51) to fit the distribution of backscatter *vs* biomass data. Backscatter signals in HH polarization presented a higher r^2 coefficient than P_{HV} datasets.

At most studies, biomass are frequently estimated by different allometric equations. Therefore, biomass data can be best fitted to the backscatter depending on the allometric equation used (i.e., if DBH and/or height are included) and depending on the polarization of the SAR data used for the analysis. Primary and secondary formations presented, in certain cases, similar P-band backscatter values, especially among sequential stages of regrowth, where the structural differences of vegetation cover are not so evident. Vegetation structural differences are influenced by local soil conditions, diversity of floristic composition, history of land occupation, drainage characteristics and recovery capacity of a certain area. Even taking into account that some omission and commission errors occured between classes, the biomass map derived from SAR data allowed the characterization and verification of the spatial distribution of vegetation cover in the study area. Tropical biomass information is essential to the quantification of sinks and sources of atmospheric CO_2 in global carbon budget studies.

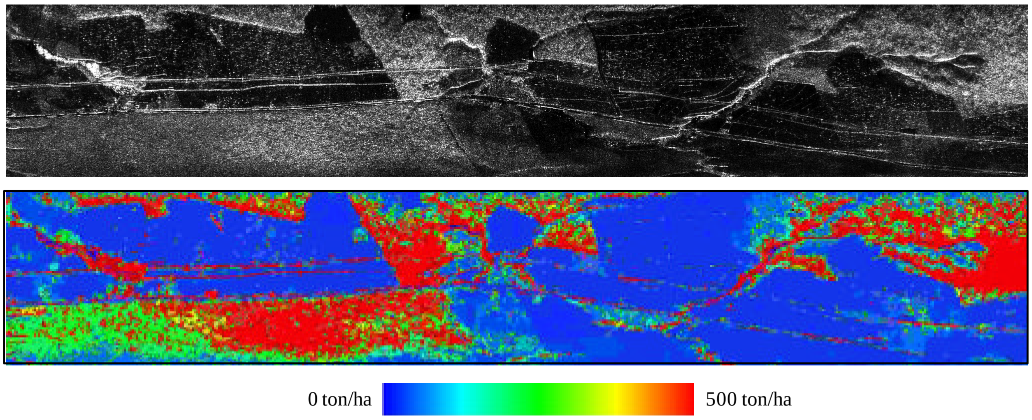

Fig. 3 - Sections of P-band image (HH polarization) and the corresponding biomass map derived from a heat capacity model.

ACKNOWLEDGEMENTS

The authors acknowledge CNPq (grants 300677/91-0, 380597/99-3, 300927/92-4), FAPEMIG (grant # CRA 00054/00); and the 8th BEC (Brazilian Arm), IBAMA/MMA and LBA office (Santarém-PA) for the logistic support. This study is a contribution to the "Science and Technology for the Management of Ecosystems" Program, from the Brazilian Ministry for Science and Technology – MCT.

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