Analysis of forest biomass variation in the Amazon and its' influence on the response of P-band SAR polarimetric data

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ABSTRACT

Radar images are presently being used in association with optical remote sensing data to characterize the different processes of land use in Brazilian Amazon region. Considering the current development in remote sensing techniques for estimating forest biomass, where L, X and C band images have their limitations, it was recently accomplished a scientific airborne mission with image polarimetric P-band imagery acquisition at lower Rio Tapajós region, Brazil. This study analyses the biomass variation of the primary forest and secondary succession and it's influence on the response of backscatter values in the P-band polarimetric images. The start of this study was the understanding of the behavior of the structural variables of the vegetation cover (measured during the field survey) and its'correlation with the backscatter data obtained from P_{HH}-, P_{HV} - and P_{VV} - band data. A statistical regression model was used to verify the relationship between biomass (estimate by different allometric equations) and P-band polarimetric data. Based on the regression equation that best fits the data sets, a biomass map was elaborated. This was done through the segmentation of the backscatter image, using Caesar 3.0 *rwseg* algorithm (based on the successive edge detecting and region growing procedures). with the $\sigma°$ of each resulting segment was converted into biomass values by the best fit function. The final goal of this P-band experiment is to improve the regional inventory and monitoring biomass dynamics, as well as landscape changes, due to human action in Amazon.

Keywords: biomass, tropical rain forest, secondary succession, P-band data, inventory, Amazon

1. INTRODUCTION

The Brazilian Amazon region occupies 5 million Km^2 and approximately 76% of this area is covered by different forest types. Studies more recent have shown that the conversion of forest areas through deforestation, burning and implantation of agricultural activities, and specially cattle raising, have risen to 600,000 Km^2 in this region. The mean rate of gross deforestation was estimated in15,800 km^2/year (INPE, 2002), although this value fluctuates widely due to such factors as the effectiveness of governmental policy in the control of forest resources. From the total area of forest destroyed in Amazon region, around 15% refers to abandoned land (non-productive), which is occupied by several stages of secondary succession. Another activity of degradation is the selective logging without a management plans, whose results of this practices are being estimated to be of 2,500 km^2/year in the *terra firme* forest areas (Santos et al., 2002a).

The human actions in the tropical forest have been conducted without planning, causing significant environmental damage (fragmentation, loss of biodiversity and reduction of soil fertilit). The decision makers on environmental issues use remote sensing data as an important tool to support the inventory and control plans of Amazon region. Furthermore, such datasets are also used as a support for the estimation of carbon emission/re-absorption in the global climate analysis, due to large scale changes of land use/land cover. New scientific studies with SAR data are being performed, in complement with a long time experience on the use of data from different optical sensor systems, in order to improve the knowledge on the characteristics and dynamics of forest. In this frame, the objective of this study is to analyze the biomass variation of primary forest and secondary succession in the P-band airborne SA polarimetric data, derived from certain structural characteristics.

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2. AREA UNDER STUDY

The study area is located at the lowe Tapajós River region (Pará State, Brazil), with the coordinates between W 58° 50' 41.68" to 59° 07' 57.18" and S 3° 15' 19.4" to 3° 15' 16.99" close to the village of São Jorge and Tapajós National Forest, along highway BR- 167 Cuiabá-Santarém. The climate, according to Köppen, is of type *Amw*, with an yearl rainfall of 1,750 to 2,000mm as well as average temperature of 26 °C. In this study area, the Latosol (Oxisol) predominate, with the occurrence of dense and open tropical forest without palms, but there are also areas with areas with different levels of regrowth. Human occupation is related mostly to subsistence agriculture (rice, cassava, maize, beans, pepper are the main products) and specially to large sections for extensive cattle raising.

3. MATERIALS AND METHODS

3.1 Acquisition of P-Band data and field survey

The SAR mission was carried out using an airborne polarimetric system, AeS-1 (*AeroSensing Radar Systeme Gmb Company/Germany*), within cooperation Brazilian Army and INPE. This airborne mission was provided P- band (λ = 72 cm) images on the HH, HV, VV polarizations, obtained with a middle frequency of 415 MHz, depression angle of 45° and average flight altitude of 3,216 m. The scenes have a pixel size with 1.5m and 0.7m for the range and azimuth resolution, respectively, for 1 look slant range image. The 1 look slant range images were used to preserve the target' statistic characteristics, and their pixel value were read by visual orientation, using field notes and Landsat-TM images as support.

Concurrently with the P-band imaging mission, a field measurement campaign was done in order to make a first physiognomic-structural reconnaissance of primary forest and secondar sucession. Given the limited time for ground surveys, a compromise was established among the sampling level performed and the number of samples acquired. Thus, both transect sampling and area sampling methods were considered for the ground data acquisition campaign. Based on former experiences (Araujo et al., 1999; Santos et al., 2002b) in studies on the association of optical and SAR data as well as data from forest inventories made in the Amazon region, the size of sample (34 plots) was limited to 10m x 250m and 10m x 100m for the primary forest and secondary succession, respectively. Each plot was positioned within a homogeneous area of vegetation typology using a GPS system. All the plots were buffered from human features (roads, pastures, etc) by a minimum distance of 50m for primary forest and 20m for secondary succession. Within each transect, some parameters were measured, such as: diameter at breast height (DBH > 5 cm), total height (H), position of each tree in the plot, and also, a botanical identification was also performed. The secondary succession areas were inventoried in order to represent three stages, namely: the initial, the intermediate and the advanced level, whose stratification considers the age of the natural regrowth as well as by certain structural characteristics and of floristic composition found in such facies. So the age intervals were established: below 5 years, from 5 to 15 years, and above 15 years for these regrowth classes, respectively.

3.2 Treatment of P-band data and ground data.

The P-band scenes were initially compared to topographic maps, for the orientation of flight strips, in order to visualize different landscapes and to facilitate plotting of points surveyed during the field campaign. Initially, the images were radiometrically corrected according to the antenna pattern using a function based on homogeneous extended areas (primary forest); and afterwards, the polarimetric calibration was done for each polarization (slant range mode), based on the 8 corner reflectors. For the precise positioning of these corner reflectors, differential GPS measurements were taken. Initially the theoretical sigma from each corner reflector was calculated and then, a correction factor (f) for these corner reflectors was generated according the equation 1 and 2 below (Santos et al., *in press*).

(Eq. 1) σ^0 *theor.* = $(4\pi/\lambda^2)$ * *Effective area / pixel area*

(Eq. 2) $f = \sigma^{o}$ theor./ (Amplitude value measured from corner reflector / sen θ_{corner})

The mean correction factor (f_m) based on the arithmetic average of the f values was obtained for HH, HV and VV polarizations. From this average correction factor the Sigma Nought ($\sigma°$) was obtained at P-band for those points sampled in the field campaign (equation 3).

(Eq. 3) $\sigma° = 20 \log [f_m$ x (measured amplitude of image / pixel)]

Statistical regression models were used to verify the variations of the behavior of the primary forest and secondary successions in the P-band polarimetric images. Initially the correlation of backscatter values with some strucutural values of the forest typology, such as: average height; percentual of trees with height<10m and height>10m; percentual of tree with 5<DBH>15 cm, 15<DBH>30cm and/or DBH>30cm per plo ; and diversity index, were investigated. In this study, we applied the Shannon index for the evaluation of floristic heterogeneity (Kent and Cooker, 1994). Afterwards, scatterplots were done showing the results of the regression models between the variables of better correlation. In this correlation analysis, the biomass variable was also included, whose values were estimated from allometric equations, based on th dendrometric parameters (DBH and H), measured during the ground survey. The following allometric equations were used, specifically for the primary forest (Eq. 4, 5) and secondary succession (Eq. 6, 7).

$\text{biomass} = 0.044 * (DBH^2 * \text{height})^{0.9719}$	Brown et al. (1989)	(Eq. 4)
$\ln(\text{biomass}) = -0.370 + 0.333 \ln(DBH) + 0.933 [\ln(DBH)]^2 - 0.122 [\ln(DBH)]^3$	Chambers et al. (2001)	(Eq. 5)
$\ln(\text{biomass}) = -1.9968 + 2.1428 \ln(DBH)$	Nelson et al. (1999)	(Eq. 6)
$\ln(\text{biomass}) = -2.17 + 1.02 \ln(DBH)^2 + 0.39 \ln \text{height}$	Uhl et al. (1988)	(Eq. 7)

The combination of some of these allometric models (considering evidently the primary or secondary forest cover) allowed to verify through regression models, that there is a better fitting between above-ground biomass and the backscatter values derived from different polarizations. The response of this airborne SAR dataset as well as biomass data were examined by regression models, using logarithmic [$y = a + b(\ln x)$] function, where the variable y = backscatter; independent variable x = biomass values; a and b = coefficient of regression.

Afterwards, based on the regression equation that best fits the dataset, a biomass map of the forest typology was elaborated based on the P-band image. In order to do that, a backscatter image was segmented, using Caesar 3.0 rwseg algorithm (NASoftware, 2002). Being so, for each resulting segment, an average Sigma Nought value was calculated, which was afterwards converted to biomass values by the best fit equation, comparatively between polarizations. The rwseg algorithm segments an image by successive edge detecting and region growing procedures. Detected edges are used to limit region growing and this process is defined by the *e* parameter which gives the possibility or not of a pixel becomes an edge. When two different regions are considered to have the same mean value then these regions ar merged in order to produce a coarser segmentation. The strenght of an edge is measured by comparing the regions on either side and the merging between the two regions is defines by the *j* parameter. Both parameters *j* and *e* were chosen by the user, and in this case, due to the thematic complexity of the scene, the values of 2.00 and 5.49 were defined, respectively.

4. DISCUSSION OF RESULTS

The analysis of structural characteristics of forest typology, such as the DBH, the height of the individual tree, number of trees and also the diversity index (related to species composition) from each transect, can improve the knowledge of the signal response from P band SAR data. During the forest inventory a number of 1,571 trees and 1,639 trees was effectively measured in primary forest and regeneration areas, respectively. Considering the field samples, a representation of the distribution of these variables (Figures 1a and 1b) was prepared with its' respective occurrence frequency for both primary forest and secondary succession. In the primary forest sections, three vegetation stores were distinguished: a discontinuous upper canopy ranging from 25 to 30m, a continuous under-store from 13 to 20m, and a dense stratum with undergrowth from 6 to 10m. The average value of biomass in primary forests (Figure 2) is of 242 ton/ha, with an average of 900 trees/ha (DBH > 5 cm). Secondary succession types present a high concentration of individuals in the lower stratum (H < 10m), whose plots present biomass mean values of 41 ton/ha, with 1,400 trees/ha. The biomass variation in regrowth areas is related to the different stages of regeneration and also to the intensity of the land use, which determines the degree of soil compaction and as a consequence affects the growth of pioneer species. Comparing the biomass values estimated for primary forest, th allometric equation from Chambers et al. (2001), presents an increase of about 20% if compared to that one of Brown et al. (1989) for secondary succession. The equation from Nelson et al. (1999) presents a similar increase when the biomass is compared with the equation from Uhl et al. (1988). It is important to point out that the equation from both Chambers et al. (2001) and Nelson et al. (1999) do have in its' formulation only the DBH as input parameter. Since the measurement of tree height is of difficult precision, specially in those sections of primary forest which have trees with a high trunk, it is recommended to use the model from Chambers et al. (2001), instead of the empirical formulation from Brown et al. (1989). The results of these variations due to different models for biomass estimate, using different SA polarizations, will be discussed in another part of this paper.

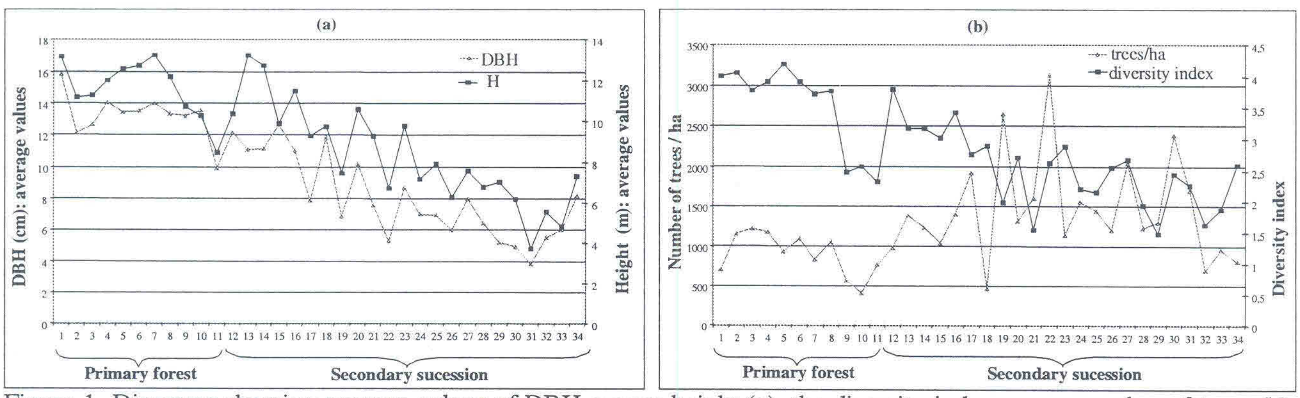

Figure 1. Diagrams showing average values of DBH *versus* height (a), the diversity index *versus* number of trees (b), for each transect of primary forest and regrowth areas.

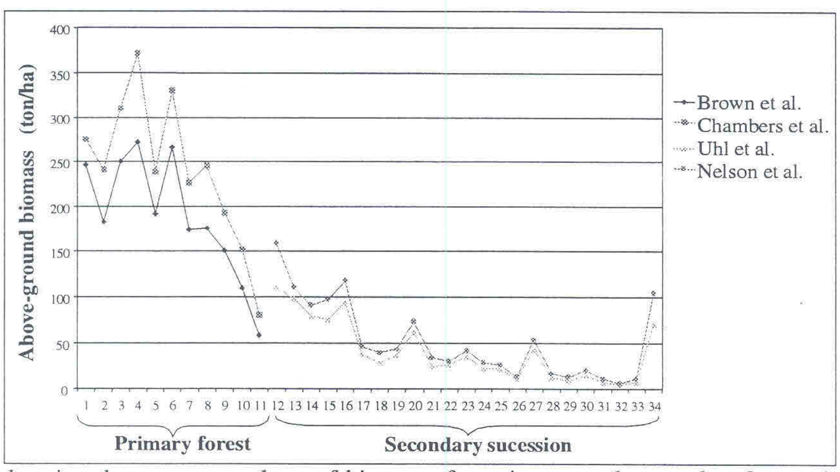

Figure 2. Diagrams showing the average values of biomass for primary and secondary forest derived from specific allometric equations.

At Table 1 one observes the correlation between the physiognomic-structural variables of the forest types studies and the polarimetric SAR P-band data. For a more detailed analysis, the variable H (Height) was stratified in two class intervals: percentage of individuals with H<10m e de H> 10m per plot. As for DBH, the separation by diameter class, considered the percentage of trees with 5cm<DBH>15 cm, 15cm<DBH>30cm and DBH>30cm per plot.

Table 1. Correlation matrix with P-band data and biophysical parameters of forest typology.

	1	2	3	4	5	6	7	8	9	10
1	1									
2	0.900239	1								
3	0.619365	0.61868	1							
4	-0.49885	-0.44424	-0.94633	1						
5	0.498847	0.444237	0.94633	-1	1					
6	0.250582	0.235466	0.40186	-0.368823	0.368823	1				
7	0.659756	0.565784	0.85156	-0.796703	0.796703	0.218865	1			
8	0.615453	0.577275	0.71243	-0.58173	0.58173	0.078766	0.659302	1		
9	0.565444	0.535882	0.79369	-0.738087	0.738087	0.130042	0.770168	0.743904	1	
10	0.553242	0.528254	0.75258	-0.685427	0.685427	0.150759	0.684178	0.847597	0.814399	1

(1) HH; (2) HV; (3) average height; (4) height < 10m; (5) height > 10m; (6) 5cm<DBH>15cm; (7) 15cm<DBH>30cm; (8) DBH>30cm; (9) diversity index; (10) biomass values.

Generally speaking, these variables present a better correlation with backscatter data at HH polarization, if compared with the other polarizations. At an isolated analysis of these structural variables, those trees with DBH above 15 cm, because they present a higher correlation value, apparently do present a significant influence on the P band response. The correlation of height with polarimetric data, independently of class intervals, is moderate (Figure 3a and 3b). The diversity index, which indicates the variability of species in the samples investigated by forest type, also show an adequate correlation.

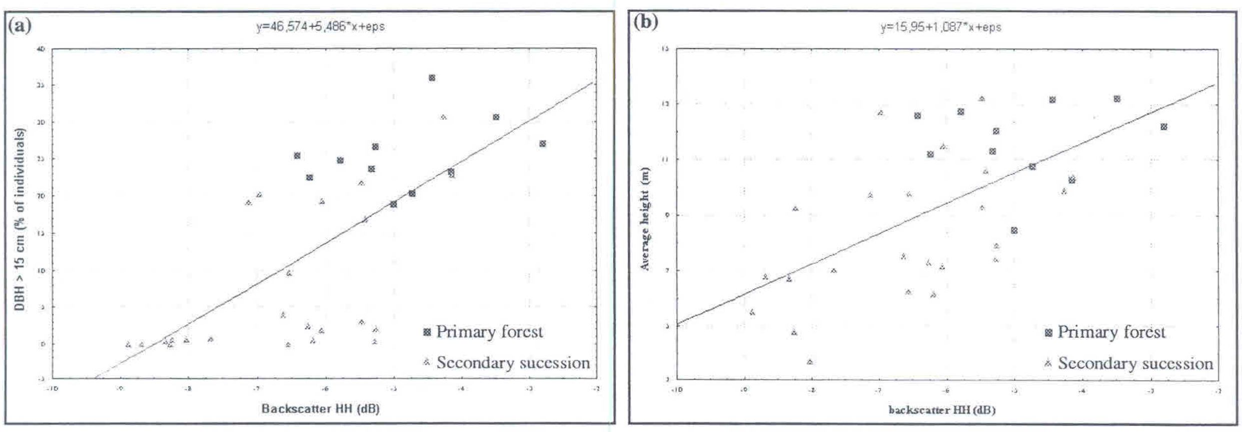

Figure 3. Scatterplot showing the P_{HH} backscatter values related to the percentage of individuals with DBH>15cm (a) and average height values (b).

The comparison between biomass values and backscatter through a regression model, shows that HH fits better than HV and VV, presenting ^{2} values higher than 0.50, independently of the mathematical formulation used to estimate the biomass. The biomass data generated by the combination of allometric equations of Chambers et al. (2001) for primary forest and of Uhl et al. (1988) for secondary succession, were just a little above those which involved the other equations. This occurred when using HH and VV polarizations (Figures 4 a,b,c). Such combination of allometric models causes different results, when using P_{HV}-band data, where biomass data derived from Browns' (primary forest) and Nelsons' (secondary succession) equation, fit better at this correlation. This seems to indicate that, at the biomass study of primary forest with cross polarized data (HV), the height component should compose the allometric estimate equation of this parameter, to have an adequate fitting of this model. The same does not apply with HH and VV polarization, where the simple use of DBH to model biomass is enough to fit ground survey and SAR data.

In the case of secondary succession, an inverse process than that of primary forest occurs. Data seems to indicate that at the P-band cross-polarization (HV) there is a certain equity at the vegetation growth, and that DBH is sufficient to model the biomass. As for polarization HH and VV, the simple change of tree height (which includes regeneration) seems to have some importance as a complementary indicator of biomass modeling. At this relation between polarimetric information and biomass, th backscatter amplitude at polarization HH and HV for primary and secondary forest (5 dB levels) is higher than those values found when using data of P $_{VV}$-band (3.5 dB levels). This would demonstrate a higher capacity of $P_{HH,\ HV}$ images to characterize better possible biometric differences of the primary and secondary vegetation facies.

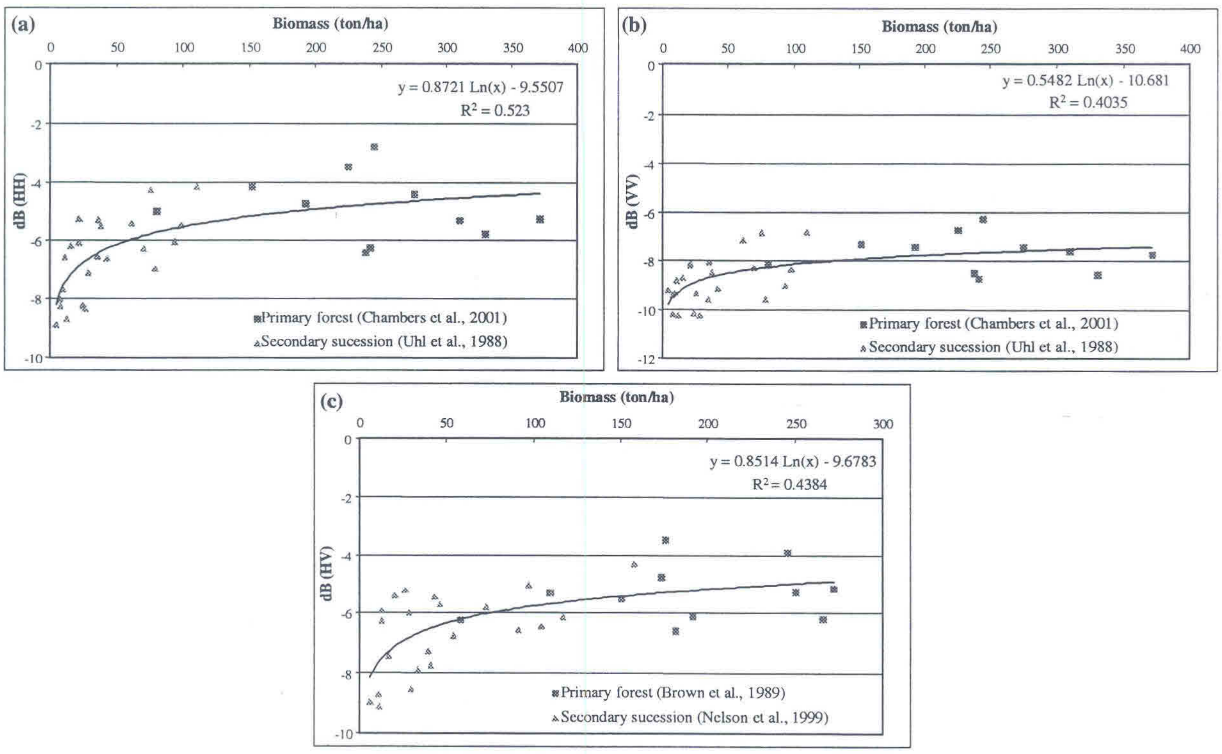

Figure 4. Relation of P-band data with above-ground biomass values from primary forest and different levels of regrowth. (a) HH polarization; (b) VV polarization; (c) HV polarization.

Based on the best fitted regression equation obtained, namely: [$y = 0.8721 * \ln(x) - 9.5505$], the empirical values of biomass in part of the area under study were mapped, as a function of backscatter from P_{HH} images (Figure 5). The legend of these maps are biomass ranges which allow the characterization and verification of the spatial distribution of primary and secondary vegetation cover. Associated to this type of information obtained from P-band images, it is very important to have a good knowledge, during field surveys, of the structural and floristic aspects of the vegetation types, whose components can influence the radiometric behavior of the radar signal. Besides that, the historical knowledge of forms and vectors of land use are also useful to understand the spatial distribution of above-ground biomass, specially in those areas of secondary succession.

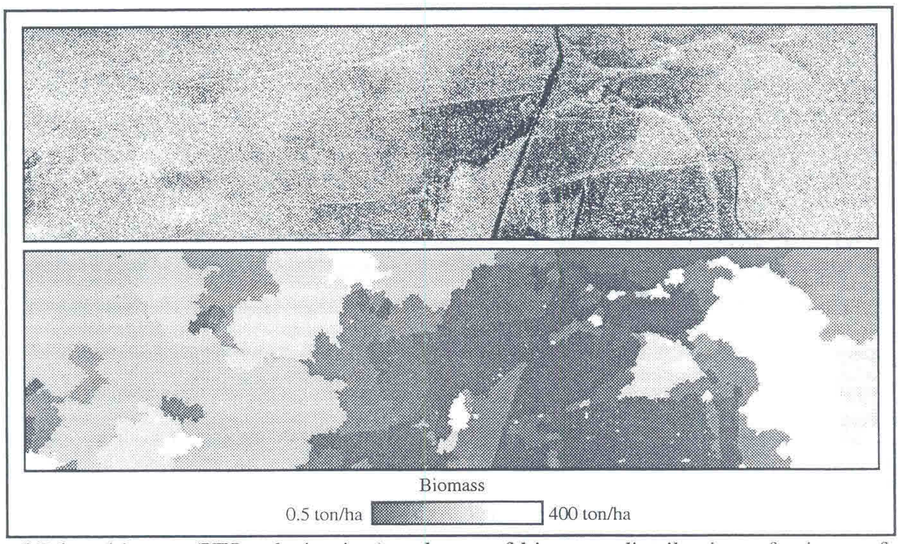

Figure 5. Sections of P-band image (HH polarization) and map of biomass distribution of primary forest and regrowth areas.

5. CONCLUSIONS

The knowledge of structures from primary and secondary tropical vegetation formations is very important for the analysis of variations found in the polarimetric values of P-band. At most studies, biomass estimates are frequently modeled by different allometric equations. Being so, there is a feeling that such biomass data can be best fitted to the backscatter data, when these allometric models include or not DBH and/or height, in accordance with the polarization used for the analysis.

Generally, the logarithm function has a moderate performance to fit the distribution of biomass *vs* backscatter data and, the HH polarization has a higher r^2 than HV and VV. Primary forest and secondary successions present some similar values of σ° at P-band, especially in those sequential stages of more advanced regrowth, where the structural differences of vegetation cover are not so evident, since they are influenced, in certain cases, by local soil conditions, diversity of floristic composition, history of land occupation and recovery capacity. The segmentation process using the Caesar 3.0 *rwseg* algorithm on the dB image, is adequate to generate a thematic map of above-ground biomass. Even taking into account that some errors occur inter-classes, the thematic map associated to biomass values derived from P-band allows a synoptic analysis of biophysical parameterization of the forest formations, which is an important tool for the regional modeling of the carbon emission and re-absorption and its influence, in studies of global changes.

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