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CANOPY STRUCTURE EFFECT ON SAR IMAGE TEXTURE *VERSUS* FOREST BIOMASS RELATIONSHIPS

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ABSTRACT

Quantifying forest biomass is of crucial importance for estimating carbon fluxes on the regional and global scale in climate change studies. Significant relationships have already been established between radar mean intensity and forest biomass, but these relationships show a reduced sensitivity to biomass variations for mature stands (about 80 t/ha and more). On the contrary, recent studies have shown that image texture is significantly related to biomass even for mature stands for a temperate, monospecific, even-aged forest the biomass of which is 140 t/ha at its highest point.

The present paper aims at extending these observations to tropical forests which represent a large terrestrial biomass pool with values higher than 450 t/ha. Radar images were acquired during the TropiSAR experiment in 2009, which took place over a tropical rain forest located in French Guiana at P band and cross-polarization with the use of SETHI ONERA airborne instrument. Three sets of treatments applied to 15 forest stands provided biomass values from 268 to 466 t/ha where permanent zones of 6.25 ha each were mapped and regularly measured.

Homogeneous patches were selected inside each of the 15 experimental stands. Statistical features were then derived for each patch: a) from grey level statistics; b) from the statistics of pixel pairs on the basis of the gray level co-occurrence matrix. It is shown that linear relationships between texture features and forest biomass are heavily influenced by stand structure and the local topography and soil of the experimental stands. But, when stands are separated on two structural groups using texture descriptors, texture/biomass regressions reveal to be very significant.

INTRODUCTION

With growing awareness of the role of forests in the global carbon cycle, the need for methods of monitoring biomass has become more urgent. Tropical forests form a large part of the terrestrial carbon pool and the carbon sources generated by deforestation in the tropics. However, little information is available on the global scale about these regions which are difficult to get to.

Remote sensing techniques are therefore of particular interest with respect to studies on global climate. In this context, Synthetic Aperture Radar (SAR) systems provide images independently of cloud cover contrary to optical systems. Moreover, SAR systems have demonstrated their potential to discriminate forest status, especially at low frequencies. In order to determine the biomass of a forest, significant relationships are therefore established between mean intensity of the backscattering coefficient (or σ^o) and biophysical variables (stand age, biomass and related variables). Carbon quantities are estimated by inferring wood biomass from forest biomass, and then converting it into carbon by using a value of approximately 0.5 ton of carbon for 1 ton of wood. However, for mature stands (about 80 t/ha and more) increasing biomass reduces the sensitivity of the σ^o/biomass relationships (1).

Studies have shown that the spatial distribution of grey levels within a SAR image may also help when characterizing vegetation cover. Texture could be used instead of the usual σ^o/biomass relationships, even for mature stands up to 140 t/ha, the highest biomass value observed for studied forests (monospecific, even-aged forest, subject to identical silvicultural practices and sampling covering all forest stages from sowing to harvest) (2).

The present paper therefore aims at testing relationships between forest biomass and radar image texture in a high biomass tropical forest. Some previous studies have used radar image texture for young regenerating tropical forests with biomass values ranging from cleared lands (0 t/ha) to mature canopies (380 t/ha) (3,4,5). In the present paper, relationships were tested in an undisturbed tropical rain forest near Sinnamary, French Guiana (5° 18' N, 52° 55' W). The Paracou experimental set-up includes six stands in untouched control areas with only natural treefall gaps and three sets of stands which are commercially logged and are associated or not with selective felling of noncommercial trees for fuel and with thinning by poison-girdling. Biomass values were estimated for each stand and range from 268 to 466 t/ha. Local statistics of σ^o were calculated as well as texture features derived from the grey-level co-occurrence matrix (GLCM).

The objective of the study is to evaluate the capacity of radar image features (local statistics, texture) to discriminate biomass classes for very high values of biomass (> 300 t/ha). The ground data set and radar data are first described (Materials and Methods). Relationships between texture features of radar images and forest biomass values are then discussed, paying attention to variations of stand structure related to stand topography (Results).

MATERIALS AND METHODS

Ground data

The Paracou experimental site is located in a lowland tropical rain forest near Sinnamary, French Guiana (5° 18' N, 52° 55 'W). It is extensively described in (6). It is covered with a moist evergreen rain forest, which has never undergone human disturbance. 15 square stands of 9 ha each were delimited on soils with superficial drainage, supposed to be the widespread type in the coastal area of French Guiana. Inside the stands, trees were monitored inside a core zone of 6.25 ha, where all trees of >10 cm dbh (trunk diameter at breast height) were localized and botanically identified.

All stems ≥10 cm dbh were regularly surveyed in each of the 15 measured stands so as to obtain tree density, height, basal area and total biomass estimations. The height of 1,400 trees was measured, the highest trees reaching 45 to 50 metres and the mean canopy height ranging between 25 and 30 metres. In undisturbed forests, the stem density of trees larger than 10 cm dbh was observed to vary from 576 to 683 trees/ha, with a mean of 620 trees/ha. Basal area varied from 29.3 to 33.0 m²/ha with a mean of 31.4 m²/ha (6).

Among the 15 stands, six (P1, P6, P11, P13, P14, P15) were in untouched control areas with only natural tree fall gaps. The remaining ones received specific treatments in 1987 and 1990. In treatment 1 (P2, P7, P9), selected timbers were extracted with an average of 10 trees ≥ 50 or 60 cm dbh removed per hectare. For treatment 2 (P3, P5, P10), they were logged as in treatment 1, followed by timber stand improvement (TSI) by poison girdling of selected non-commercial species, with about 30 trees ≥40 cm dbh removed per hectare. In treatment 3 (P4, P8, P12) stands were logged as in treatment 2 for an expanded list of commercial species, with about 45 trees ≥40 cm dbh removed per hectare. An additional stand (P16 in Figure 1) of 25 ha was dedicated to the study of the undisturbed forest ecosystem in 1991/1992: it is not accounted for in this study.

Biomass values for each stand were estimated using allometry developed for moist tropical forests (7) based on two predictors: wood specific gravity and dbh. Biomass values estimated in 2007 are given for each stand in Table 1.

The topography consists of gently undulating landscapes with a very dense hydrographic system generally oriented SW-NE. Paracou is located in the "terra firme" region in the northernmost part of the hilly area. The relief of the site consists of small elliptic hills separated by narrow (<5m wide) sandy waterbeds. The altitude varies from 5 to about 45 m above sea level (6). Topographic information was available (6) and completed by lidar data (campaign 2008), which were transformed *via* a digital elevation model.

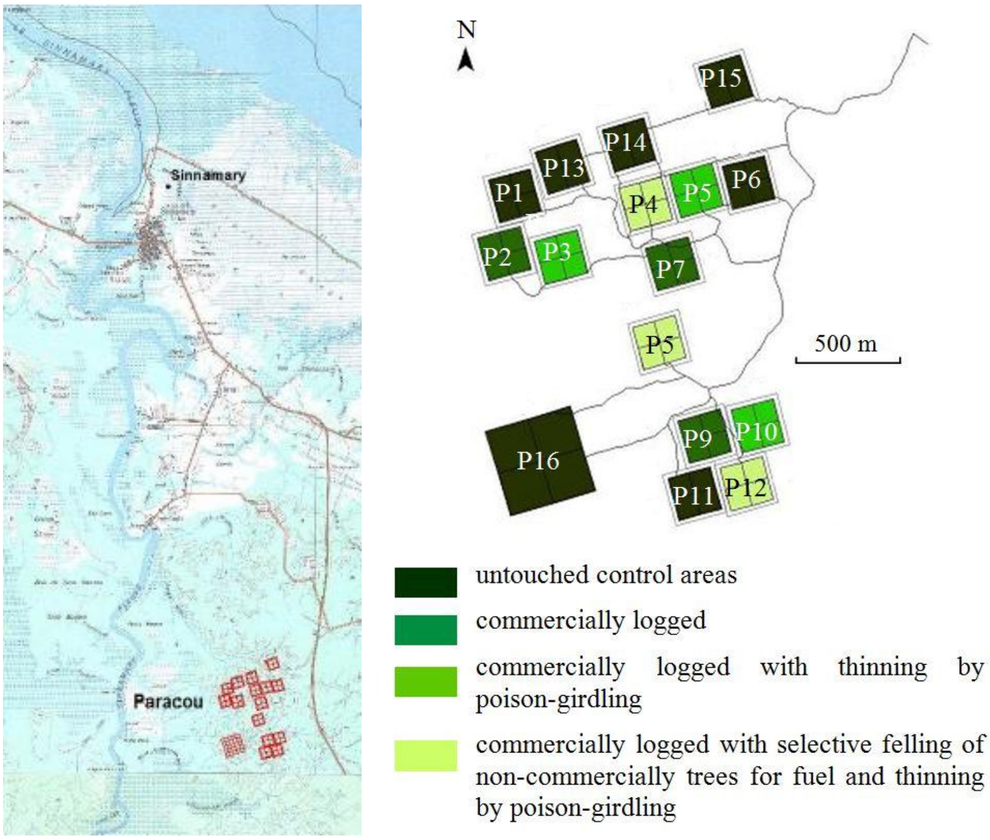

Figure 1: Location of the Paracou experimental site and description of the experimental stands.

Table 1: Biomass values estimated for each experimental stand.

	Stand	Biomass (t/ha)
Undisturbed forests	P1	389.8
	P6	466.0
	P11	428.5
	P13	436.5
	P14	434.4
	P15	438.3
Logged stands (Treatment 1)	P2	351.3
	P7	409.1
	P9	359.6
Logged stands (Treatment 2)	P3	308.0
	P5	310.7
	P10	318.0
Logged stands (Treatment 3)	P4	297.2
	P8	266.7
	P12	318.2

Radar data

Radar images were acquired during the TropiSAR experiment in 2009 over the Paracou experimental site using the SETHI ONERA airborne instrument (8). This system gives fully polarimetric SAR images at P band (centre frequency 440 MHz), L band (centre frequency 1300 MHz) and X band (centre frequency 9600 MHz). The airborne system used for the radar acquisitions (SETHI) is a new generation SAR developed over the past three years, to be compatible with small/medium aircrafts for remote sensing applications (8). The first version of the system (2007) included P, L and X bands with fully polarimetric SAR and a potential for single pass interferometry at X band. P and L systems rely on fully digital signal generation and a new UHF-VHF system was tested in 2008.

During the experimental campaign over French Guiana, two radar systems at P band and at L band were operated. The P band waveform ranged from 260 MHz to 460 MHz, with 200 MHz of bandwidth allowing of a slant range resolution of 0.7 m which corresponds to a ground resolution of 0.95 m at mid-range (45° incidence). Tests were performed in this paper with the P band acquisition 0402 (August 24) at cross polarization known to provide the best sensitivity of σ^o to forest parameter variations. A Region of Interest (ROI) file identifies the different stands with in-situ measurements.

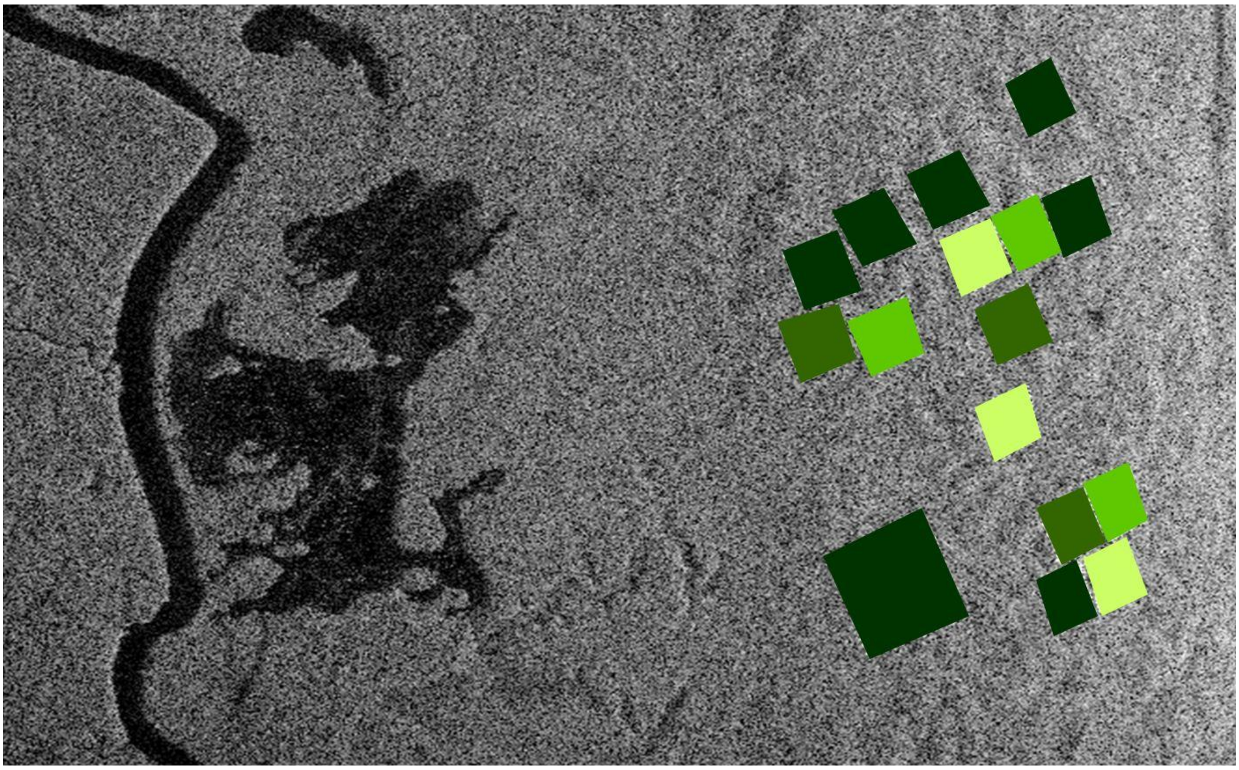

Figure 2: Radar image (P band, polarisation HV) and localization of the regions of interest with experimental stands.

RESULTS

Calculation of texture features

Estimations of the biomass were carried out on the whole surface of the experimental stands (6.25 ha). Texture calculations on the corresponding radar image zones were therefore performed.

For each of the 15 stands, two sets of texture features were then calculated on 100x100 pixel windows on the radar image. The first set of calculations was derived from the σ^o distribution: variance, skewness, kurtosis and entropy. The second set was derived from the grey-level co-occurrence matrix (GLCM) established for horizontal joined couples of pixels (9): energy, contrast, homogeneity, correlation and entropy.

For texture calculations, the SAR image was transformed into intensity values and GLCM were rendered symmetrical and were normalized for each radar zone corresponding to the experimental stands. The quality of the linear regressions between biomass and the texture features was characterized by the determination coefficient (R^2) and the t-student factor (Table 2).

*Table 2: Coefficients of determination (R^2) between estimated biomass and SAR image texture features derived from the intensity distribution (variance, skewness, kurtosis, entropy) and from the GLCM (contrast, entropy, homogeneity). Student tests were performed and ** (resp. *) indicates significant regressions for p-values < 0.05 (resp. 0.1).*

		R^2	*t*-student
Local statistics	variance	0.19	1.7
	skewness	0.13	1.4
	kurtosis	0.28	2.2**
	entropy	0.13	1.4
Texture from the GLCM	contrast	0.20	1.8*
	entropy	0.15	1.5
	homogeneity	0.20	1.8*

Figure 3 shows a relative linear correlation between biomass and texture features, but the dispersion of values is too great with respect to the biomass range to consider these relationships as a useful tool for biomass retrieving. It emerges that factors other than biomass variation influence the image texture, especially variations of forest structure in each of the 15 stands.

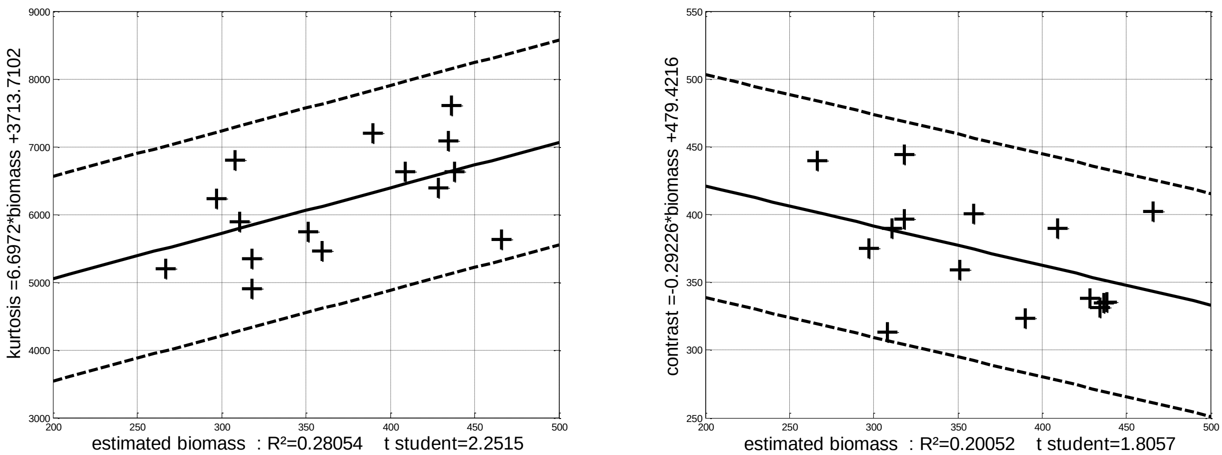

Figure 3: Linear fits between estimated biomass of experimental stands and texture features calculated on the SAR image (P band, HV). On the left: Kurtosis derived from the intensity distribution. On the right: Contrast derived from the GLCM.

Influence of the overall structure related to stand topography

Stands are located in a region with gentle topography and parts of them are occupied by lowlands or slopes or bottomlands (10). It appears that the topography influences the local species composition and the growth of the major species and it is likely to modify the roughness of the canopy surface (6,10). Specialization in seasonally flooded habitats may explain patterns of adaptive behaviours in many tropical tree genera and may change their growth and density, and generally the structure of the community (11).

Biomass values were estimated on the total surface of each 6.25 ha stand, thus integrating variations of species composition and growth related to topology and soil morphology. Edaphic constraints have a direct impact on the density and size of the trees, as well as on tree species distributions, which influences the structure of the stands.

The floristic composition of the forest is related to the soil morphology (watertable depth) and topographic situation. Pedological classes were therefore defined, making use of a digital elevation model established on all the stands as follows: bottomlands (altitude ≤5 m and slope ≤5°), hillsides (slope >5° whatever the altitude) and hilltops (altitude >5 m and slope = 0).

As a consequence, variations of tree densities of up to 100 t/ha are observed inside the same experimental stand depending on whether they are measured on the plateau or in the bottomlands. Due to the internal characteristics of each stand, density values shift from 576 trees/ha-1 (P2) to 683 trees/ha (P11), while basal values go from 29.3 m²/ha (P2) to 33 m²/ha (P12). These variations are equivalent to the mean basal area removed by the logging operations (6).

The topography can therefore induce variations of biomass equivalent to or higher than the different treatments applied to the stands.

According to their density and basal areas, experimental stands were classified by three overall structure classes or blocks (6). Block 1 contained the most heterogeneous stands (P1 to P3 and P8), characterized either by a lot of small trees (P1), a lot of trees in intermediate classes (P2) or a lot of big trees (P3 and P8). Block 2 (P6, P7, P10 and P12) gathered stands which differed according to the weight of intermediate and large diameter classes. Block 3 (P4, P5, P9 and P11) was the most homogeneous, grouping mainly stands where small diameter classes were highly represented. Structural information was not available for P13, P14 and P15.

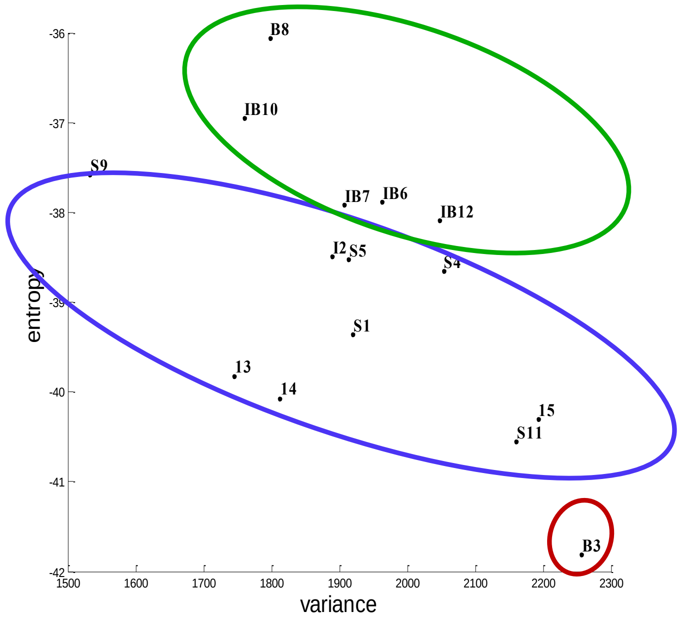

Figure 4: Entropy vs variance based on GLCM for the 15 experimental stands. They are referenced by their structure classes as defined in (6): S for small classes, I for intermediate, B for large trees.

*Table 3: Coefficients of determination (R^2) between estimated biomass and SAR image texture dividing stands in two groups according to their structural characteristics. Significant correlations are indicated as *** (resp. ** and *) for p-values < 0.01 (resp. 0.05 and 0.1). NdF is the number of degrees of freedom for each group.*

		Group "big", NdF=4		Group "small", NdF=8	
		R^2	*t*-student	R^2	*t*-student
Local statistics	variance	0.10	0.75	0.26	1.55
	skewness	0.54	2.40*	0.06	0.67
	kurtosis	0.37	1.72	0.43	2.31**
	entropy	0.44	1.98	0.51	2.72**
Texture from the GLCM	energy	0.50	2.21*	0.66	3.69***
	contrast	0.43	1.93	0.61	3.31**
	entropy	0.48	2.13*	0.64	3.53***
	homog	0.54	2.42*	0.60	3.23**

If structural classes are considered, it is shown (Figure 4) that texture features have the capability of discriminating structural categories of stands: those with intermediate and large trees (B and IB) and those which are dominated by small trees (S and I) apart from P3 which has a very different behaviour. P13, P14 and P15 seem to be similar to stands characterized by a large class of small trees.

On this basis, it arises (Table 3) that texture/biomass relationships become much encouraging once applied separately on both structural groups "Big" ones (P6, P7, P8, P10, P12) and "Small" ones (P1, P2, P4, P5, P9, P11, P13, P14, P15).

CONCLUSIONS

It has been hypothesized that SAR image texture (as a measure of canopy unevenness) could be positively related to tropical forest biomass up to and beyond the saturation point of the backscatter-biomass relationship. The objective was, therefore, to use the spatial characteristics of SAR backscatter, firstly to obtain a better correlation between backscatter and biomass, and secondly to increase the biomass range that could be estimated from SAR data.

In the present study, texture/biomass relationships were tested in an undisturbed tropical rain forest in French Guiana with control stands and stands which received different levels of thinning in 1984 and 1990. Airborne SAR data were used at P band and HV polarization.

First results show that there indeed exists a correlation between biomass and the texture of the radar image, but regressions are poor due to a large dispersion of data relative to the biomass value range which is related to the stand structure. Inside each stand, variations of topology and soil morphology determine local variations of the structure (tree size, density, floristic composition) which influences the texture of the radar image.

However, it is observed that texture features have the capacity to discriminate two classes of stands, which corresponds to structural classes: trunk size distribution and occurrence of big trees. Then, when applied separately to each structural group of stands, very significant relationships between biomass and radar texture were obtained. These results open perspectives to deduce forest biomass from SAR images as they give an alternative to the inversion methods based on relationships between SAR radiometry and forest parameters.

Future work will focus on the validation of the method. Texture variations inside each stand should be further explored with respect to its topography by selecting homogeneous zones (lowlands, bottomlands, slopes) and discrimination of structural classes will be tested on the entire forest.

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