RETRIEVING FOREST BIOMASS FROM THE TEXTURE OF SAR IMAGES

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ABSTRACT

The objective of this paper was to study the use of texture features to retrieve forest biomass, which is of crucial importance to global carbon studies. Texture features are derived from: a) $\sigma°$ distribution statistics (variance and entropy), and b) the grey level co-occurrence matrix (energy, entropy). Radar images were acquired at P band cross and parallel polarisations using an airborne radar system built at the French aerospace laboratory and flying over an experimental forest at the north of the Landes region (France). This forest is documented by the French National Institute of Agricultural Research (INRA) as a controlled homogeneous test site: a single species, even-aged forest, subject to identical silvicultural treatment and the sampling of ten stands which cover all forest stages from sowing to harvest and provides sampled data on age, height, trunk *dbh* (diameter at breast height) and density measurements. Biomass was then calculated from ground data by means of allometric equations for these ten stands using stand age, *dbh* and density estimations.

Forest biomass was inferred from image texture using two methods. The first directly deduced forest biomass from image texture on the basis of biomass/texture regressions. As a second step we tried to avoid the use of structural measurements to calculate the biomass (stand *dbh* and density), so that *dbh* was inferred from texture and density was deduced from stand age. Total and stem biomass were then recalculated.

It was concluded that some of the texture indicators were significantly correlated to growth parameters (age, trunk *dbh*, biomass) displaying regularly linear variations. Moreover, the uncertainty related to these estimation methods was less than 20% of the biomass value, whichever way biomass is retrieved from texture (directly or through a *dbh*/texture regression). Texture could therefore be used as an alternative characterisation technique for plantation forests where intensity-based relationships are showing decreased sensitivity for mature stands.

INTRODUCTION

For use in climate change studies (carbon fluxes) and also for forest management, variations in standing biomass are a key parameter to quantify the sequestration and release of terrestrial carbon. Until now, data on forest biomass was obtained using forest inventories with additional allometric relationships established on the basis of destructive harvesting experiments, if these were available. The obstacles to producing reliable biomass estimates, from the local scale to the continental scale, are widely acknowledged. Moreover, the results of studies based on comparisons of biomass maps produced by using different methods for the spatial extrapolation of *in situ* measurements have varied markedly in terms of both spatial distribution and biomass values (1).

As an example, errors in biomass estimations at the European level resulted from the application of three independent approaches, i.e. ecosystem modelling, forest inventories and the upscaling of ecological data; the optimum agreement in findings only reaching 25% at best (2).

Remote sensing techniques have been the subject of particular study during the past 10 years with respect to studies on global climate that have involved detailed estimates of carbon variations at a global scale. Aperture Radar (SAR) systems have demonstrated their potential to discriminate forest status, especially at low frequencies, and useful relationships have been established between the radar mean intensity and biophysical variables (3,4).

However, image intensity-based relationships have displayed decreasing sensitivity for mature stands i.e. forest biomasses larger than about 80 t ha^{-1}, even at P band (1). For this reason, Champion *et al.* (5) decided to evaluate the potential of SAR image texture and were able to show that image texture significantly varies with stand growth, even in the case of mature stands in an even-aged, cultivated pine forest.

The aim of the present study was thus to evaluate the potential ability of texture to retrieve forest biomass (total biomass and stem biomass) from polarimetric P band SAR images. The evaluation was performed on a set of ten experimental stands which were sampled and measured, the ground dataset and radar data being described in a first section (Materials and Methods). The age was known for each stand on the experimental site and structural measurements were performed on ten of these stands inside the zone viewed by the radar system.

Biomass values were then derived from the trunk *dbh* (diameter at breast height) and stand age, together with additional stand density information obtained by using allometric equations. Two methods are thus proposed to retrieve biomass values based on radar texture information, and the resulting uncertainties relative to the biomass values retrieved then are discussed.

MATERIALS AND METHODS

Radar images

Radar images of the experimental Nezer forest in the Landes region were acquired using the RAMSES system (Figure 1). RAMSES (Radar Aéroporté Multi-spectral d'Etude des Signatures) is an airborne SAR operating at P band (0.427 GHz) which was developed by ONERA (National Office for Aerospace Studies and Research, or Office National d'Etudes et Recherches Aérospatiales). RAMSES was flying onboard a Transall C160 aircraft equipped with high accuracy GPS for trajectory monitoring. The radar data thus analysed were high resolution complex polarimetric data acquired on 21 January 2004. The radar view angle varied over the image from 10° in the near range to 60° in the far range.

The emitted power was more than 600 W and a high bandwidth of 70 MHz enabled a pixel size of 3.21×2.46 m², where 2.46 m was the radial projected resolution or range distance (at -3dB) and 3.21 m the azimuth projected resolution (Figure 1). A calibration site was set up in the Nezer forest, with specific reflectors developed for the P-band. The RAMSES P-band flight was performed under good meteorological conditions (6).

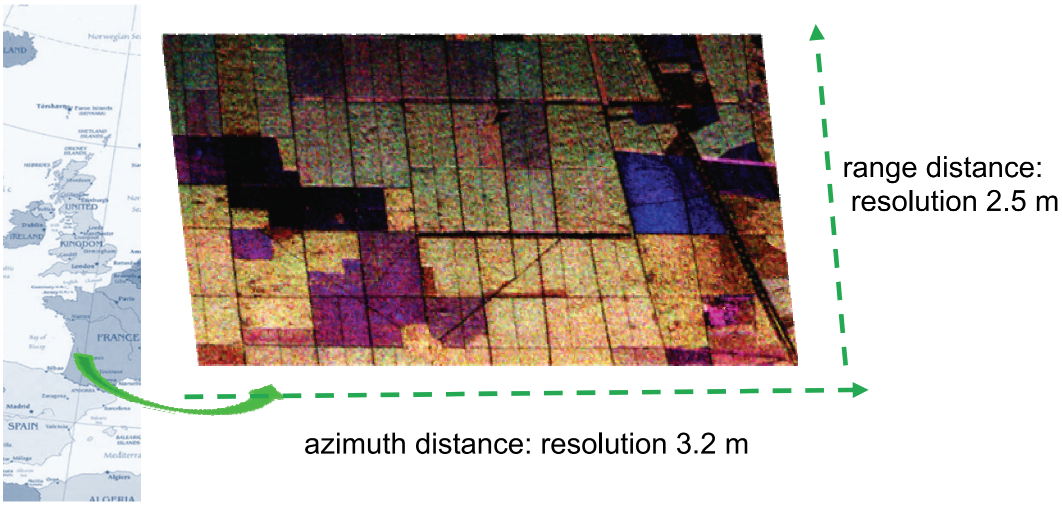

Figure 1: Localisation of the experimental site and an example of a radar image (P band, HV) of the Nezer forest in Les Landes (SW France).

Each image corresponded to four, single-look complex images (HH, HV, VH, VV) associated with a rectangular weighting window. Radar cross section imaging and real parts were transformed into σ^0 values as a function of view angle and resolution surface.

Ground dataset

The INRA experimental Nezer forest is located at the north of the Landes forest and contains well-defined planted stands of maritime pines (Pinus pinaster Ait.) all subject of identical silvicultural treatment (Figure 1). The pine trees had been sown or planted in rows with a 4 m spacing over a nearly flat surface and had a broad range of ages (from seedlings to 51 years). Each stand is rectangular in shape, delimited by fire protection clearings or access tracks.

The ages of the forest stands were available from the INRA geographical database and the structural parameters of 13 stands were measured to produce estimates of total height, density and mean trunk *dbh* (7). Based on these measurements, the total biomass and trunk biomass of each stand was then estimated from allometric equations established for each aerial tree compartment using destructive measurements (8,9). Therefore, the total biomass was the "above-ground biomass" including trunks, branches and leaves and excluding the understory and litter.

The total biomass and stem or trunk biomass were therefore calculated as a function of trunk dbh and stand age as follows (8,9):

$$biomass_{per\ tree} = a_1 \cdot dbh^{a_2} \cdot age^{a_3} \qquad \text{(Eq. 1)}$$

with :	a_1=0.0938	a_2=1.992	a_3=0.3298	for total biomass
	a_1=0.0211	a_2=2.284	a_3=0.3549	for trunk biomass (wood)
	a_1= 0.01521	a_2= 1.346	a_3 = 0.8773	for trunk biomass (bark)

stem biomass = trunk wood biomass + trunk bark biomass

Values were established at the tree scale in kg of dry matter. They were transformed into t ha^{-1} using the stand density values measured for each stand. The resulting stem biomass and total biomass values are referred to in this paper as the 'observed' stem and total biomass.

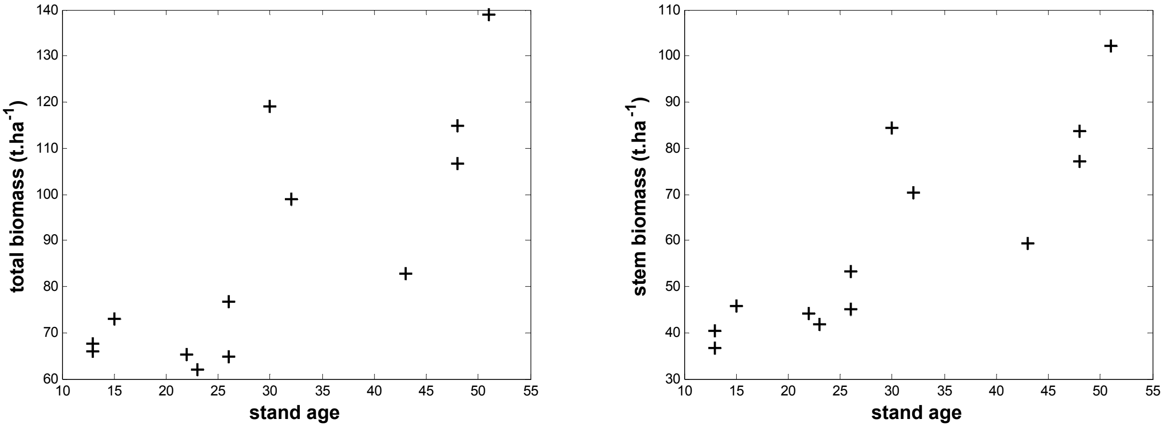

Figure 2: 'Observed' total and stem biomass estimated from ground data using allometric equation 1.

Total biomass values ranged from 61.9 t ha^{-1} (value for the 23-year old stand) to 139 t ha^{-1} (for the oldest stand, 51 years old). Stem biomass values ranged from 36.6 t ha^{-1} (13-year old stand) to 102.2 t ha^{-1} (oldest stand).

Biomass values increased linearly with stand age but displayed broad 'natural' variability related not only to measurement uncertainties but also to stand characteristics (thinning, soil heterogeneity, fertility, etc.). As an example, the difference in total biomass values between the 30- and 32-year old stands was 20 t ha^{-1} (119-99 t ha^{-1}, Figure 2), while it was 12 t ha^{-1} (77-65 t ha^{-1}) for the two 26-year old stands.

Both the trunk *dbh* and the stand density (values which were necessary to calculate biomass) also varied with stand age (Figure 3). The stand density decreased regularly with stand age and could be modelled as shown in Figure 3 with a standard deviation of error of 25 tree ha^{-1}. However, the trunk *dbh* varied linearly with age, although this variation displayed a rupture at stand ages between 30 and 40 years which could be linked to changes in silvicultural treatments over time.

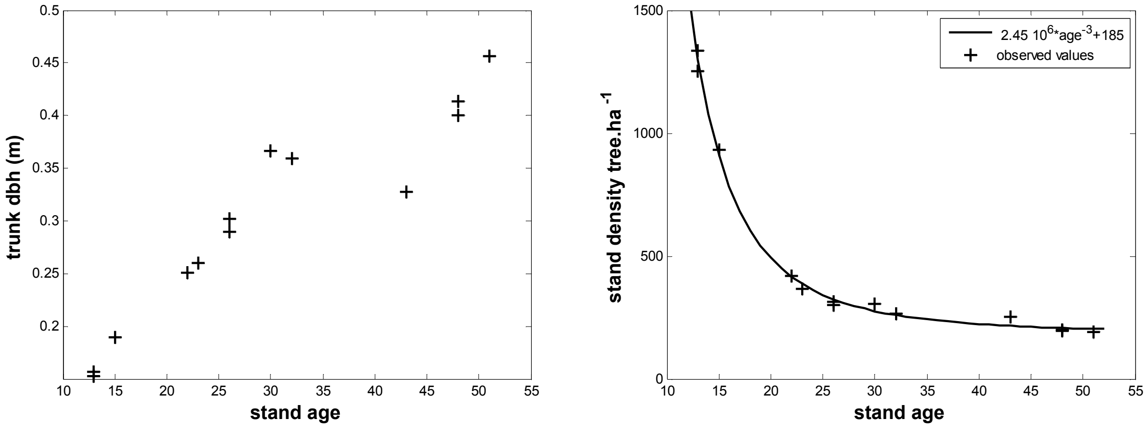

Figure 3: Left: observed trunk dbh versus stand age; right, calculated and observed stand densities versus stand age; the mean std is ±25 tree ha^{-1}.

Calculation of texture indicators

Of the 13 experimental stands, only ten aged between 15 and 51 years were situated within the zone covered by the SAR image. In each of these 10 stands, a patch is selected from the radar image in a homogeneous zone of the stand so as to eliminate any disturbances resulting from storm damage, fire, etc. These 10 patches were then squared and rendered equal in size (60×60 pixels).

Two sets of texture features were calculated (10). The first derived from the σ^o distribution: variance, skewness, kurtosis and entropy, while the second one derived from the grey-level co-occurrence matrix (GLCM) established for horizontal joined couples of pixels: energy, contrast, homogeneity, correlation and entropy.

Texture features were therefore calculated for each homogeneous 60×60 patch extracted from the radar images at cross and parallel polarisations on the 10 forest stands for which ground structural measurements were available. For texture calculations, σ^o SAR images were transformed into intensity values and GLCM were rendered symmetrical and were normalised.

RESULTS

Regressions were performed between texture features and ground data for the 10 stands: stand age, observed stem and total biomass, trunk *dbh* and stand density. Only texture indicators that provided the best linear fits are shown in Table 1.

R^2 values were indicative of the quality of linear relationships between these texture indicators and the various forest parameters. The best R^2 values (Table 1) were found for cross-polarized images, which was consistent with other findings in the literature (1). The trunk *dbh* was strongly correlated (p-values<0.001) to variance and entropy1, and the stand age to variance. Stem and total biomass were significantly (p-values<0.005) correlated to variance (and entropies for stem biomass).

We observed that regressions involving forest parameters related to trunk growth (trunk *dbh*, stem biomass) produced better R^2 values than global parameters (total biomass, density). This was especially true for the trunk *dbh*, which was significantly correlated to all texture features. This result is also consistent with previous studies which had established that the backscattering coefficient at P band was principally responsive to large scatterers such as large branches and trunks. However, regressions based on stand density displayed lower determinant coefficients. The best relationships obtained are shown in Figure 4.

*Table 1. Determinant coefficient R² values of the linear fits between observed forest parameters (age, trunk dbh, stand density, total and stem biomass) and SAR image texture indicators derived from the intensity distribution (variance and entropy1) and from the grey-level co-occurrence matrix (energy and entropy2). In grey: values of R²>0.60. Student tests were performed and *** (resp **) indicates significant regressions for p-values<0.001 (resp 0.005).*

Growth parameter	SAR image	variance	entropy1	energy	entropy2
Stand age	VH	0.77***	0.66	0.60	0.63
	HH	0.34	0.48	0.46	0.52
	VV	0.50	0.53	0.55	0.52
Total biomass	VH	0.67**	0.63	0.58	0.62
	HH	0.42	0.49	0.47	0.52
	VV	0.37	0.37	0.33	0.32
Stem biomass	VH	0.72**	0.68**	0.63	0.66**
	HH	0.45	0.52	0.50	0.56
	VV	0.44	0.44	0.41	0.40
Trunk dbh	VH	0.81***	0.75***	0.69**	0.70**
	HH	0.42	0.54	0.52	0.57
	VV	0.60	0.64	0.65	0.63
Stand density	VH	0.54	0.47	0.43	0.42
	HH	0.22	0.30	0.28	0.31
	VV	0.58	0.62	0.66	0.64

The sample (10 stands for which ground measurements were available within the radar image) was limited but the results revealed very high levels of significance and no bias. It thus appears from Table 1 and Figure 4 that the SAR image texture at P band varied regularly with forest stand growth. Variations were linear for the whole range of growth parameters and were significant at confidence levels superior to 99.9%.

In light of these results, it could be inferred that two methods could be used to retrieve forest biomass data from texture: either directly by using biomass/texture regressions (Figure 4c and d) or indirectly by using *dbh*/texture regression (Figure 4a).

Direct retrieval of biomass from texture

The regressions shown in Figure 4c and d were used to retrieve stem biomass and total biomass directly from texture. Total biomass and stem biomass could therefore be deduced from the following linear equations:

$$\textit{total biomass} = 1.186 \cdot 10^5 \left(\text{variance}\right) - 321.08$$

$$\textit{stem biomass} = 1.01 \cdot 10^5 \left(\text{variance}\right) - 286.51$$

The estimated standard errors (ErrorEst: Figure 4) were 11.4 t ha^{-1} for total biomass and 8.2 t ha^{-1} for stem biomass.

Calculating biomass using dbh values obtained from texture

In view of the quality of the trunk *dbh* vs. variance regression (Figure 4a), biomass could also be calculated using *dbh* values obtained from texture with the allometric equation 1.

In fact, the *dbh*/texture regression appeared to be better than biomass/texture regressions: R² was higher and residual points were more homogeneously dispersed (Figure 4), which could be consistent because wave/trunk interactions are dominant in the P band.

The mean *dbh* was then calculated using the linear equation with variance (Figure 4 a):

$$trunk\ dbh = 489.18 \cdot (\text{variance}) - 1.38$$

The estimated standard error (ErrorEst: Figure 3) was 0.0354 m.

Moreover, in cultivated forests such as the test site, stand age could be considered as known. Biomass could therefore be calculated at the tree scale using allometric equation 1.

Stand density was necessary to calculate biomass at the stand scale. Stand density could also be deduced from image texture, but the best regression (VV polarization density=*f*(energy)) produced an R^2=0.66 and a standard deviation of the error of 188 tree ha^{-1} (Table 1). Density could therefore be deduced from the stand age using the relationship given in Figure 3.

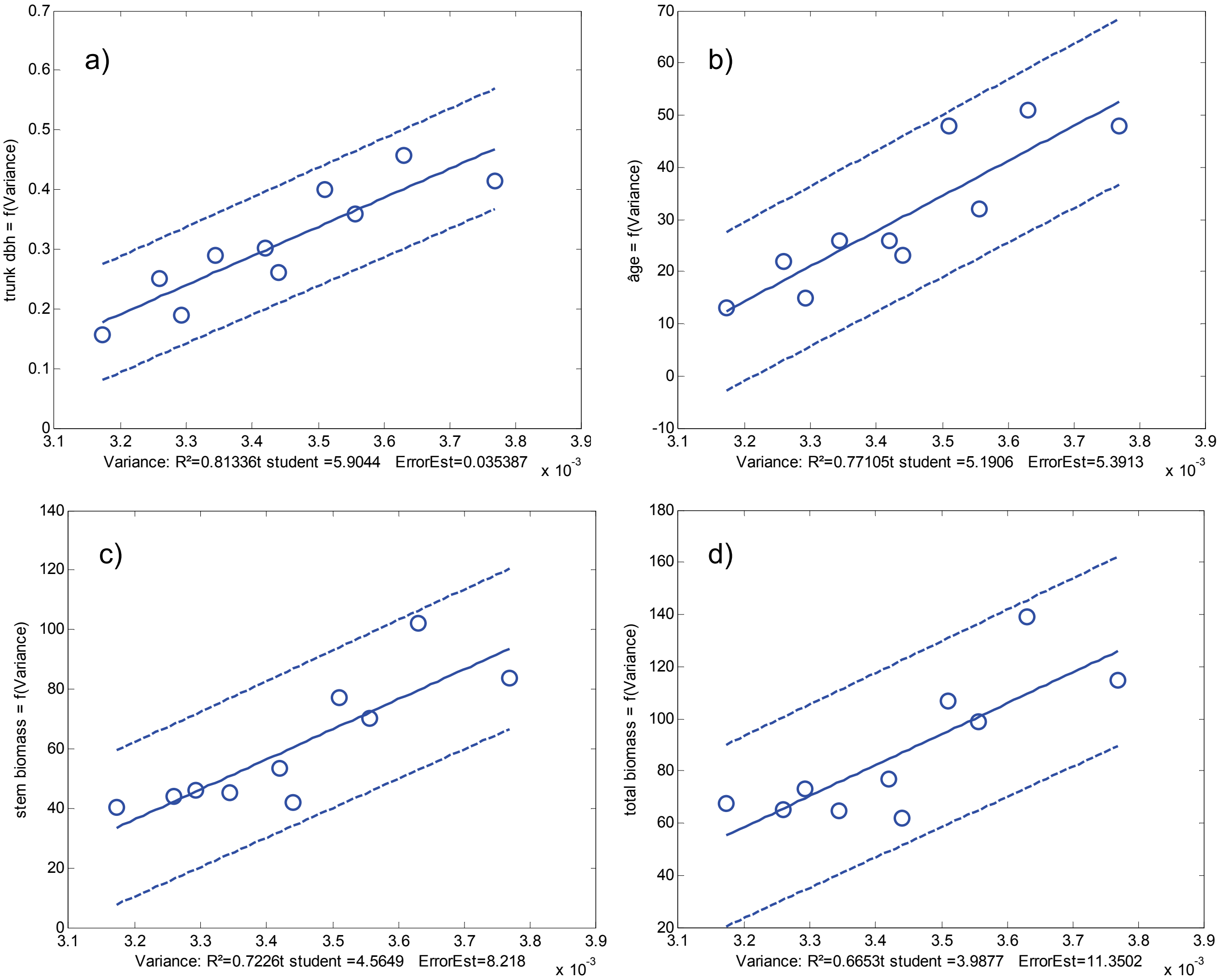

Figure 4: Linear fits between structural parameters related to forest growth and intensity variance of the P band, VH polarisation: a) trunk dbh; b) stand age; c) stem biomass; d) total biomass. R^2 is the determinant coefficient, and Student's t-test values were always higher than 3.69 ($t_{0.005}$ for 9 degrees of freedom). ErrorEst gives an estimate of the standard deviation of the error in predicting a future observation of a forest parameter using the texture indicator as the regressor (dotted lines).

The total biomass and stem biomass values calculated using the two methods (direct: *biomass*=*f*(texture) and indirect: *biomass*=*f*[*dbh*=*g*(texture))] are plotted in Figure 5 with respect to the observed values. The direct method produced mean errors that were half the errors resulting from the indirect method (Table 2). In all cases, the mean error was lower than 24 t ha^{-1} for the total biomass and 19 t ha^{-1} for stem biomass, which is less than 20% of the mature stand values.

Table 2: Mean errors for total biomass and stem biomass calculated from SAR image texture using two methods. Direct method: biomass is directly inferred from image intensity variance. Indirect method: biomass is obtained using allometric equation 1 with the dbh values inferred from image texture, while stand density is deduced from stand age.

Mean error	Stem biomass	Total biomass
Direct method	8.1 t ha^{-1}	11.5 t ha^{-1}
Indirect method	18.9 t ha^{-1}	23.7 t ha^{-1}

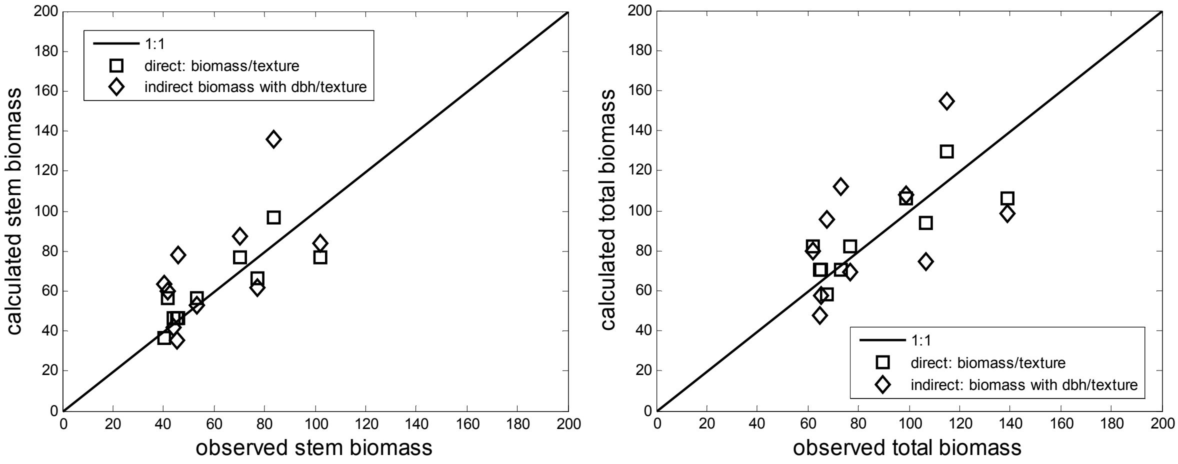

Figure 5: Values calculated with regard to observed stem biomass (left) and total biomass (right) using direct and indirect methods.

This direct method could therefore be very useful if the regression (biomass=f(texture)) is proved to be robust in different contexts; i.e. using different SAR images and/or a variety of forest types.

The indirect method gave rise to larger errors. However, they still seemed reasonable considering the problem of estimating forest biomass values by any means. Moreover, the validity domain of allometric equations is known and it is a little bit easier to measure *dbh* values than biomass values involving both *dbh* and density estimations.

CONCLUSION

In general, estimates of forest biomass are very difficult to obtain, despite their importance to climate studies and forest management. Information has traditionally been generated from forest inventories and additional allometric relationships (when available), which requires complicated ground measurements and further extrapolation to a regional scale. SAR systems have demonstrated their potential to discriminate forest stages from bare soil to old stands, especially at low frequencies. However, despite the fact that useful relationships have been established between the radar mean backscattering coefficient and forest growth parameters, few studies have so far utilised image texture. This paper shows that radar image texture could be extremely valuable to characterise forest growth parameters, particularly in cross-polarised P band images. In the context of the experimental site studied here (single-crop cultivated forest), intensity variance or entropy, and GLCM energy or entropy, were able to supply highly significant linear relationships with stand age, trunk *dbh* or biomass. However, these relationships were strongly dependent on the general structure of the forest, which remains specific to the site (i.e. dependent on topography, soil texture and fertility, etc.) and silvicultural practices (dimensions and orientation of planting ranks, degree of thinning and frequency, etc.). Nevertheless, if these regressions were validated in different contexts, it would be possible to infer forest biomass from texture indicators with uncertainties of less than 20% of the values.

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