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Determination of forest biomass using remote sensing techniques with radar images. Pilot study in area of the province of Huelva. REDIAM

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Abstract: Biomass is a very important forest resource in Andalusia. "Forest Biomass in Andalusia" web tool, developed by the Andalusian Government, provides information about the location and biomass stock for the main pine forest species. It is important to mention that information needs to be regularly, quickly, effectively and inexpensively updated. These requirements could be covered with the help of Earth Observation technologies. In this project, radar images have been acquired from ALOS-PALSAR sensor from different years (2008 and 2010) over two pilot areas located in Huelva. The aim of the study has been to develop a methodology to estimate wood volumes based on the statistic correlation between radar signal and wood volume, variable extracted of forest management plans contemporary to images. As result, correlations of 0.8 and 0.7 have been obtained for pine and eucalyptus respectively. Forest biomass has been calculated using species-specific allometric equations. Three key sources of information have been used: a sample of plots distributed homogeneously, an accurate digital terrain model and a current forest map. Furthermore, the study of the variability of estimated volumes between these dates has been carried out. Methodologies obtained could be extrapolated to the whole region.

Key words: remote sensing, radar, ALOS-PALSAR, backscattering, aboveground biomass.

Determinación de biomasa forestal mediante la utilización de técnicas de teledetección con imágenes radar. Estudio piloto en ámbito de la provincia de Huelva. REDIAM

Resumen: La biomasa es un recurso forestal de gran importancia en Andalucía. Por ejemplo, la aplicación WEB "Biomasa Forestal en Andalucía" (Consejería de Medio Ambiente y Ordenación del Territorio, 2014) informa al usuario acerca de la ubicación y existencias de biomasa de las principales especies forestales de pino. No obstante, se trata de una información que demanda ser actualizada periódicamente, con rapidez, eficacia y a bajo coste, requisitos que podría cubrir la tecnología basada en Observación de la Tierra. En este artículo se presenta un estudio piloto donde se ha evaluado la tecnología radar, concretamente el sensor ALOS-PALSAR (*Advanced Land Observing Satellite - Phased Array type L-band Synthetic Aperture Radar*), para medir la biomasa forestal de dos montes públicos de Huelva en Junio de 2008 y de 2010. El objetivo ha sido desarrollar una metodología para la estimación de volúmenes maderables a partir de la correlación estadística de la señal radar con datos coetáneos de volumen maderable, variable extraída de

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planes de ordenación forestal. Como resultado, se han logrado correlaciones en torno a 0,8 y 0,7 en pino y eucalipto respectivamente. Para la obtención de biomasa a partir de los volúmenes estimados se han usado ecuaciones alométricas específicas para cada especie. Tres son las fuentes de información claves: una muestra de parcelas homogéneamente distribuidas, un modelo digital del terreno preciso y un mapa forestal actual. Por otro lado, se ha llevado a cabo el estudio de la variabilidad de volúmenes estimados entre las fechas mencionadas. La metodología obtenida podría extrapolarse a todo el territorio regional.

Palabras clave: teledetección, radar, ALOS-PALSAR, señal retro-dispersada, biomasa aérea.

1. Introduction

Biomass as a forest resource is becoming increasingly important for the profit of the Andalusian forest areas (Order of December 29th 2011, which regulates the use of forest biomass for energy purposes). On one hand, due to the energy efficiency that it provides, it constitutes a fuel that also presents clear environmental advantages and acquires great social value by creating jobs, uniting rural areas as well as revitalizing land use (Technical meeting "Forest biomass: opportunities, expectations and needs of an emerging sector". AAEF, 2011: "1st Workshop on Forest Biomass in Andalusia: Development of the energy uses of Forest Biomass in Andalusia. Baeza (Spain), November 25th 2011). On the other hand, biomass allows an estimation of the fixation of carbon derived from accumulated growth of plants that can be directly related to the process of Global Climate Change. Thus, in order to make accurate estimates of climate changes in the future, it is necessary to have a deep knowledge of the quantity and distribution of the fixed biomass (Andalusian Strategy on Climate Change (started in 2002); Andalusian Plan of Action for Climate (started in 2007)). Therefore, it is necessary to know how much biomass is lost or is accumulated over time, and where these events occur.

Currently, estimates of biomass in Andalusia are obtained from allometric relationships derived from accurate forest inventories at local level (either foot field inventories or from highly detailed LiDAR data), but the update rate may be insufficient for estimating biomass of large areas as required by the environmental management at regional level. In fact, it is a demand which the scientific community has been widely investigated for, using Earth Observation data from satellites and culminating with *Biomass* (Le Toan, 2015), future mission of the European Space Agency. It is a radar system capable of penetrating the canopy surface to count the carbon fixed by the forests of the planet by measuring the components that contributes most to the total biomass (trunk and branches). Currently, in the design phase, the sensor will pulse at the electromagnetic spectrum P band, 70 cm. There are different satellites operating in the X, C and L bands (3 cm, 5.6 cm and 23.6 cm respectively) on board missions like TerraSAR-X, CosmoSky-Med, Sentinel 1 A/B, Radarsat 1/2 or ALOS-2 among others. But, to date, there is no satellite radar operating in P band. The only P band data available to date are from air flights (E-SAR and F-SAR). These data have been used to show that the backscattering is positively correlated with biomass, height and basal area at stand level (Hussin *et al.,* 1991; Dobson *et al.,* 1992).

However, saturation of backscattering from a given volume occurs, whose value depends on the band used. This saturation is bigger the greater the wavelength.

Therefore, the X, C, L and P, ordered from lowest to highest wavelength bands, P is the band which allows higher estimation of concentrations of wood volume (Le Toan *et al.,* 1992).

Imhoff in 1995 corroborated previous studies and examined the thresholds of the saturation of backscattering for bands P, L and C regarding global biomass data. Given the absence of P band onboard satellite, L band is presented as the best option.

In this way, images acquired with sensor PALSAR (Phased Array type L-band Synthetic Aperture Radar) onboard ALOS (Advanced Land Observing Satellite), mission developed by JAXA (Japan Aerospace Exploration Agency), have been used for this study. It consists of a polarimetric sensor that captures in three modes, Single Polarisation FBS (HH or VV), Dual Polarisation FBD (HH + HV or VV + VH) and Full polarimetric Quad (HH + HV + VH + VV), which can carry out scans with nominal incidence angle from 9.9° to 50.8°.

From the initiative Kyoto and Carbon (K & C), JAXA formed scientific teams to provide information to the International Environmental Conventions, the Environmental Conservation and the Carbon Cycle, as whole called CCCs (ALOS Kyoto & Carbon Initiative Science Plan, 2008). Since 2007 the annual ALOS congresses are the best shop window for dissemination, among other topics, the results achieved in forest issues: estimation of wood volume, aerial biomass and improvement algorithm. Several studies on boreal, moderate or semiarid climate (Santoro *et al.,* 2009; Suzuki *et al.,* 2013; Cartus *et al.,* 2012; Tanase *et al.*, 2014) have shown the capacity of FBD HH / HV mode to estimate volumes with bark. Other studies have shown that HV polarization is more sensitive than HH polarization to the growth of forests, or what is the same, to the volume with bark and the biomass (Hamdan *et al.,* 2015).

These studies indicate that PALSAR is able to evaluate volumes with bark, however, modeling the backscattering signal requires to know what mechanisms of dispersion of five possible (Richards, 1990) come into play in forest stands (i.e.: surface and volume canopy, trunk surface, ground surface, ground-canopy, trunk-ground). The radar beam penetration is higher in L band than other shorter bands. Therefore, the volume of the canopy is an attenuating element, while the trunk and large branches are the elements that most contribute to the backscattering (Le Toan *et al.,* 1992, Leckie and Ranson, 1998). The trunk-ground and ground-canopy interactions depend on the structure of the coverage and the thickness of the vegetation (Kasischke *et al.,* 1997).

Once dispersion mechanisms are known, researchers have managed empirical and semi-empirical models to model the backscattering. Empirical models have no theoretical foundation and are based on experimentation. These models do not explain a system, but provide a relationship between variables derived from a base table. Lucas *et al.,* 2004, showed that they were suitable to estimate structural variables using the C, L and P bands. In this study, an empirical model has proved satisfactory for Eucalyptus groves. However, a well distributed large sample of field data (plots) will be essential for upscaling from local to regional level (Zianis *et al.,* 2005).

This handicap may be prevented if semi-empirical models are used, as they settle into a physical theoretical basis (Trevett, 1986). A model used by many authors and here also used in Pine trees is the Water Cloud Model (WCM), which describes the relationship between backscattering and dasometric variables of a forest (Attema and Ulaby, 1978).

This model assumes the suitability of scattering elements (drops), i.e., they have identical cross section of attenuation such that the total energy is the incoherent sum of the energy scattered by each of the elements. In a forest cover, the canopy is a medium consisting of identical scattering elements (crowns) and homogeneously distributed on a horizontal plane that is the ground. Part of the beam incident on the crown bounces back to the sensor, and the remainder will be transmitted trying to reach the ground at the same time it is attenuated on the way. The WCM can be summarized in:

- Ground surface dispersion and forest volume dispersion.
- The vegetation is a homogeneous environment and gaps between trees are not included.
- The homogeneous environment is ideally formed by identical particles.
- The kind of double-bounce reflections are not included.

Askne *et al.,* 1995, included the gaps in the canopy transmissivity. This variable, the surface backscattering and volume backscattering are the three variables to be determined. This model has been used with satisfactory results in pine forests. To estimate the biomass through empirical or semi-empirical models is necessary to use field data to calibrate these models.

Frequently, wood volumes from forest inventories are used as field data. In this study, aboveground biomass is estimated, which consists in two main components, wood (timber) and firewood (branches and leaves). Prediction equations of each biomass component have been obtained from a wide data base gathered from the revision of different studies around the world (including the Iberian Peninsula).

2. Objectives and study site

The main objective is to analyze the viability of using radar technology to estimate aboveground forest biomass of main tree species in Andalusia. The aim is to determine a useful methodology which may be applied on the extrapolation to large areas and which may provide a response to the regional management of this resource, including the possibility of carrying out studies at different dates (multi-temporal analysis of forests). Thus, forest inventories could be carried out more frequently (higher refresh rate) and at lower costs. Developed methodology has allowed estimating volumes from radar images acquired in 2008 and from forest inventories data, using semi-empirical models based on radar echo of the canopy forest. Furthermore, this methodology has been implemented using images of 2010 in order to estimate the variation of biomass in the study area between two dates.

For this work, two different areas of the province of Huelva were selected (Figure 1): an area (in the north) has been called Zone-A, located in Sierra Pelada and Rivera del Aserrador (municipal districts of Aroche and Cortegana) and another called Zone-B (in the south), located on the Mount "Baldíos de Beas", the core forest "El Cobujón" and the Mount "Las Cumbres de Santa Maria" (municipal districts of Beas, Calañas, Valverde and Trigueros respectively).

The choice of these areas is justified by several reasons. On the one hand, the mountains studied have been inventoried at the dates of interest and therefore the availability of field data exists. On the other hand, they are representative of the typical areas of eucalyptus plantations in Andalusia, as well as the predominant species of pines at the regional level. The genuses studied are *Eucalyptus* spp., *Pinus* spp. and *Quercus* spp.

It is important to say that Andalusia is characterized by the heterogeneity of species distribution over most of the territory. Also, this is a representative sample of Andalusia alternating large areas of Eucalyptus groves, Pines trees and Holm oaks in valleys with others in large slopes.

3. Material and Methods

3.1. Material

The two study areas were monitored on June 23rd 2008 and June 29th 2010. On each occasion, two ALOS-PALSAR scenes were required (path - row: [7] - [740/750]), captured in ascending geometry and FBD HH / HV mode. At an angle of incidence of 34.3°, the images present an azimuth and range resolutions of 9.36 and 3.17 meters respectively. Figure 1 shows the radar scenes covering the province of Huelva. Zone-A (red) is located north and Zone-B (blue) is located south.

Table 1. Characteristics of the acquired images.

ID Product	Date	Orbit	Path/Row	Resolution (Range/ Azimuth)	Acquired images and Polarization	Incidence angle (scene center)	Geometry
ALPSRP128640740	20080623 22:50:32	12864	7 / 740	9.36 / 3.17	1 HH /1 HV	34.3°	Ascending
ALPSRP128640750	20080623 22:50:40	12864	7 / 750	9.36 / 3.17	1 HH / 1 HV	34.3°	Ascending
ALPSRP236000740	20100629 22:54:16	23600	7 / 740	9.36 / 3.17	1 HH / 1 HV	34.3°	Ascending
ALPSRP236000750	20100629 22:54:24	23600	7 / 750	9.36 / 3.17	1 HH / 1 HV	34.3°	Ascending

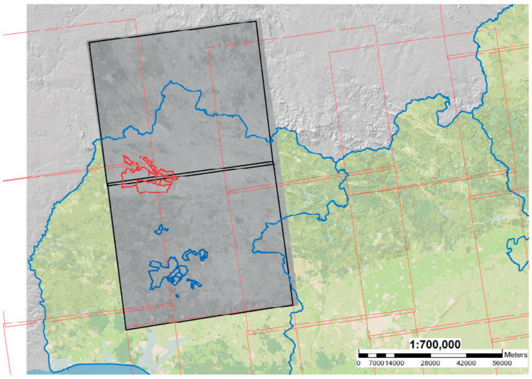

Figure 1. Coverage of the radar scenes over Huelva. North in red, location Zone-A; south in blue, Zone-B.

Wind or rain can modify a forest's radar signal response (Santoro *et al.,* 2008). Being one of the goals to compare aboveground biomass estimated in 2008 to the number estimated in 2010, scenes were selected with a difference of 6 days and in similar weather conditions, no precipitation and low wind gusts.

The following are the details concerning the field data employed in the study. Zone-A accounts for an approximate area of 14500 ha, for which a Forest Management Plan, conducted by classic inventory based on field surveys in 2007-08, was available. The plots are subdivided into the usual dasocratic units (mountain, working circle, compartment, stand). The design of the field data collection methodology was to obtain maximum accuracy at a district level. The number of inventoried plots is 2286. The range of volumes with bark included is between (0.202-368.451) m^3/ha while the height range is of (5.040-39.260) m. In Zone-B, there was no Forest Management Plan but a species mapping was obtained from forest inventory based on a LiDAR project, conducted in 2008, and irregular circular plot sampling (10 m and 25 m radius). The initial number of inventoried plots is 203. The range of volumes with bark included is between (0.176-56.650) m^3/ha and the height range is (2.03-19.03) m.

In Figures 2 and 3 (Methodology section) are details of the sampling methodology design in both zones.

As reference mapping information, a Digital Elevation Model (DEM) 10×10 m^2 was available for Zone-A, from the Aerial Ortophotography National Plan (2007 and 2009), and a DEM 1×1 m^2 obtained from LiDAR in 2008 for Zone-B. Both DEM's were used for the analysis of the land relief and terrain slopes in order to characterize these areas, as well as for the geometric correction of radar images. PNOA 0.5 m orthophotography (natural color) of Andalusia from 2007 to 2009, were employed for the capture of points necessary for the geometric correction of radar images, segmentation and delimitation of working units, and analysis of results from the estimation of biomass between study dates. The Spanish Land Cover Information System (SIOSE) in Andalusia (scale 1:10000) was used to verify segmentation results from orthophotos.

3.2. Methods

3.2.1. Radar Image Processing

Images were received with a processing level 1.1, which corresponds to single-look complex (SLC). The set-up for the modeling involves the following steps: Multilooking, Coregistration, Filtering, and Geocoding. To this purpose the SARScape tool was employed. The Multilooking process transforms the complex image into backscatter signal, which is the ratio of the power emitted and received by the sensor. For both HH and HV polarizations, the default SARScape calibration factors were used (Shimada *et al.,* 2009, Earth Observation Research Center, 2009). In addition, the original images were resampled in azimuth by averaging five pixels, obtaining almost square pixels: 15.85 m in azimuth and 16.60 m in range. This step enhances the radiometric resolution at the expense of spatial resolution.

The co-registration process is the next essential step as the study was performed on two different dates, in order to correct the translational and rotational displacements. Considering that the analyzed mountains present a terrain with steep slopes, two data sources were added: an accurate DEM and ground control points (GCP). The DEM was resampled to 15 m and the PNOA Orthophotography was employed for obtaining accurate GCP. The co-registered subpixel achieved was 1/10.

The next step consisted in the Filtering process for reducing the speckle effect, inherent to any active system that emits coherent pulses, as is the case for SAR or LiDAR. This effect was slightly corrected during the azimuth resampling at the Multilooking process, but was insufficient. Frost and Lee filters are commonly used; they are based on multiplicative models and local statistics (Lee, 1980, Frost *et al.,* 1982). The study employed a Frost filter which used 5×5 pixels moving window.

The last step consisted in the Geocoding process which transforms the back-scattered signal from the current SAR geometry, named ‘slant range’, to a cartographic reference system. As previously mentioned, the study area presents a complex topography and in order to achieve an optimal geometric and radiometric calibration, GCP and an accurate DEM are required. A single GCP obtained by employing a 0.5 m Orthophoto proved enough to rectify possible inaccuracies in orbit due to the high precision in orbits we account for to this date. Backscatter was orthorectified with DEM, which was also used to generate the mask known as the layover/shadow. Layover refers to areas where the angle between the normal of the dispersing element and the beam incidence angle, known as local incidence angle (lia), is negative, while shadow refers to areas where the lia is greater than 90 degrees. Negative lia values indicate that these surfaces, be it either hillsides or other elements, are oriented facing the beam and have a slope greater than incidence angle, which results in backscatter saturation. However, values exceeding 90 degrees lia indicate that these surfaces are oriented in a fashion which doesn’t allow the beam to illuminate them. A radiometric standardization was applied to the range direction in order to reduce the effect of incidence angle. This effect is an intrinsic component of the backscatter which needs to be compensated and is accentuated in the presence of topography (Ulaby and Dobson, 1989). Once all the above indicated corrections were carried out, the images were georeferenced according to WGS84 reference system, UTM 30N, units in decibels (dB) and a final spatial resolution of 15 m. Since there were two scenes covering the study area, four mosaics were generated to continue the process: two per year and one for each polarization, HH and HV.

3.2.2. Defining working units

Backscattered signals coming from forests are extremely casuistic due to the fact that more than one dispersal mechanism appears. A study at pixel level would be a mistake as there would be no consistency in comparing biomass or any other measure between two different dates. However, averaging this signal at a stand or compartment level is an appropriate measure since these forestry entities are employed in forest management according to geographical and typological homogeneity criteria. To establish appropriate units for each zone, an analysis was carried out considering land relief and other factors involved.

Zone-A is complex in terms of its topography, with an average slope of 19.51 degrees, reaching a maximum slope of 59.69 degrees. Given that the radar beam captured information at an angle of 34.3 degrees, it leads to the appearance of layover/shadow effects in the backscatter, as explained in the previous section, and as a consequence pixels affected by this cannot be worked with. On the other hand, a Forest Management Plan was available for Zone-A, as indicated in paragraph 3.1, in which 2286 plots were inventoried. The data were grouped into 467 compartments possessing inventoried information, with an average area of 31.2 ha, being the smallest of 18.7 ha. After eliminating the cases presenting layover/shadow, a sufficiently representative sample was available for using compartments as working units. The possibility of using stand was also studied. Although initially there were 1140 stands with inventory data, 26% of these had less than 1 ha surface, and considering that the resolution of the images was 15 m/pixel, there would be stands with less than 45 pixels, along with the masking of all the ones affected by layover/shadow, the sample could not be considered representative for the study.

Zone-B has a much less complex orography with an average slope of 11.82 degrees, resulting in fewer layover/shadow situations. Therefore, working at a stand unit was considered as the best alternative. A total of 203 field plots, derived from 2008 LiDAR flight, were initially available. Since no Forest Management Plan was available, a new distribution of stands was generated from the segmentation of PNOA orthophotography using as reference the species mapping available,

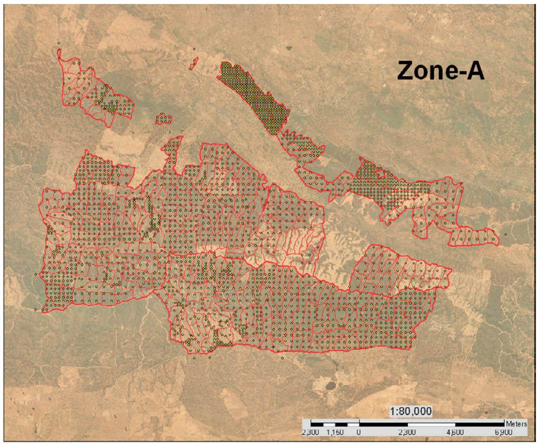

Figure 2. Distribution of field plots (yellow) and delimitation of compartments (red) in Zone-A.

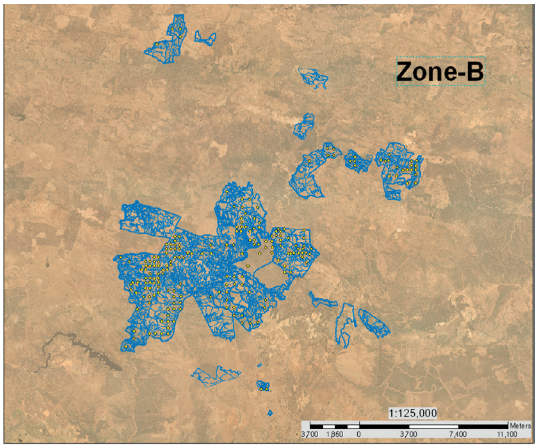

Figure 3. Distribution of field plots (yellow) and delimitation of stands (blue) in Zone-B.

resulting in 1826 stands with an average size of 3.56 ha. Figures 2 and 3 contain the distribution of field sampling (plots) and the distribution of compartments and stands in the study areas.

3.2.3. Methodological approach

As indicated in the introductory chapter, HV polarization is more sensitive to forest growth than HH polarization, i.e. to volumes with bark and to biomass, for this reason the methodology was developed using backscatter HV polarization. As for models, it was observed throughout the experimental procedure that the backscattering behavior pattern differs in relation to volume measured depending on which family of species is being monitored. As a result, two approaches were defined: for pine trees a semi-empirical WCM model was employed; in the case of eucalyptus trees, a previous study was conducted on eucalyptus groves (Lucas *et al.,* 2004) which showed that by using the L-band PALSAR sensor a linear regression model was what best correlated backscatter with ground truth in these masses; throughout the project it was evidenced that the same applies to Holm oak groves, so a linear regression model was also used.

The first task consisted in carrying out a training process of the selected models for each year. Beginning with 2008, the first step was to select the compartments/stands from Zone-A/ Zone-B which accounted for field data. Prior to the selection, the following operations were performed: masking of the non-forest use pixels and of pixels presenting layover/shadow effects; erosion of compartments/stands with 15 m (pixel images) to eliminate edge effects, unproductive stands or paths; plots located within 15 m of the edge of a compartment/stand were not considered to avoid errors due to image georeferencing or to GPS. Plots which presented no mixture of species were selected, as the presence of several species caused a loss in correlation (Figure 4). In the case of Zone-A, Holm oaks were not studied since there were no compartments that presented the species exclusively. After these considerations, of the initial 467 compartments, 123 were studied in Zone-A, with an average area of 31.73 ha, of which 93 consisted of eucalyptus groves and 30 consisted of pine tree groves. In Zone-B, a total of 154 stands proved appropriate for study, presenting an average area of 3.56 ha, corresponding to 42 eucalyptus groves, 92 pines tree groves and 47 Holm oak groves.

The next step was to generate pairs of values [backscatter, field volume] and sort them from the lowest to the highest volumes. The odd pairs of values were selected to train the models while the even pairs of values were selected for validating them. This was to ensure that the entire range of volume values were represented in the training

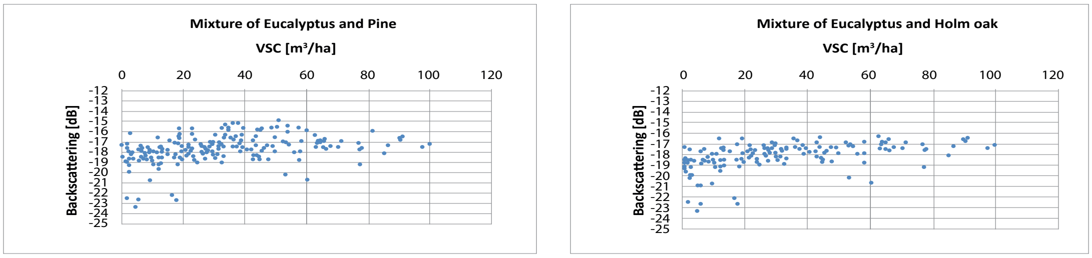

Figure 4. Absence of correlation between backscatter and volume in compartments with mixed species in Zone-A. VSC is the volume without bark.

and validation procedures. Volumes including bark were used for the Pine tree groves and Holm oak groves while for Eucalyptus groves, the volumes didn't include the tree barks.

Therefore, two models were trained in Zone-A, a WCM for Pine tree groves and a linear regression for Eucalyptus groves, and two models in Zone-B, a WCM for Pine tree groves and a linear regression for Holm oak groves. The trained model for Eucalyptus groves in Zone-A was also used for the same species in Zone-B. This was done to test whether the situation had any critical effect on the use of an empirical model (Zianis *et al.,* 2005) for estimating volumes or, by the contrary, if a linear relationship between backscatter-volume could be used for Eucalyptus groves and could be extrapolated to the whole region, which will be discussed in the results section.

Figures 5 and 6 show the correlation of backscatter against volume in both zones.

For training the models in 2010, the lack of field data was solved by extrapolating the volumes from 2008 to 2010 using the annual increase collected during the 2008 campaign for Zone-A and IFN3 growth equations for Zone -B. The premise for the study is that the areas have not been affected by factors such as wildfires, felling, etc. and therefore assuming that the resulting estimated volume for 2010 would be higher than for 2008, a fact which will be discussed in the results chapter. Concerning Holm oak groves, no growth equation existed, reason for which the volume was only estimated for 2008. Figure 7 shows the correlation of backscatter against volume in both zones.

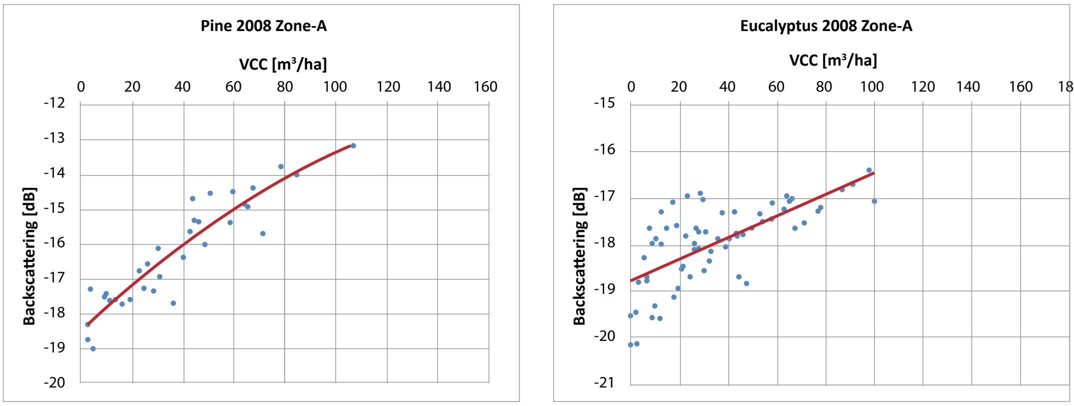

Figure 5. Training of models for Zone-A in 2008: The dots show the correlation between the backscatter measured in HV cross-correlation images and volume obtained by forest inventory (sampling area); the graphs represent the modeled backscatter (the trend is polynomial in the case of Pine trees, while the trend is linear for Eucalyptus groves). VCC is the volume with bark; VSC is the volume without bark.

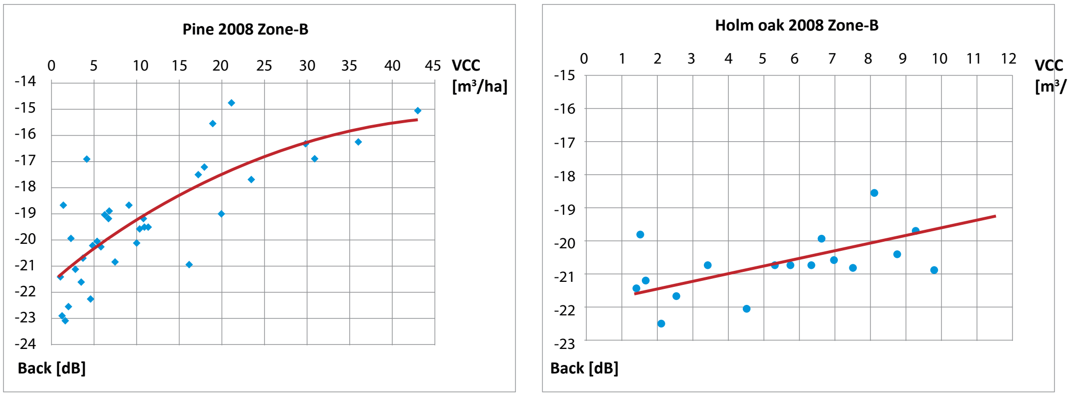

Figure 6. Training of models for Zone-B in 2008: The dots show the correlation between the backscatter measured in HV cross-correlation images and the volume obtained by forest inventory (LiDAR); the graphs represent the modeled backscatter (the trend is polynomial in the case of Pine trees, while the trend is linear for Holm oaks). Eucalyptus training is the same as in Zone-A (stands in Zone-B have been used for validation purposes only). VCC is the volume with bark.

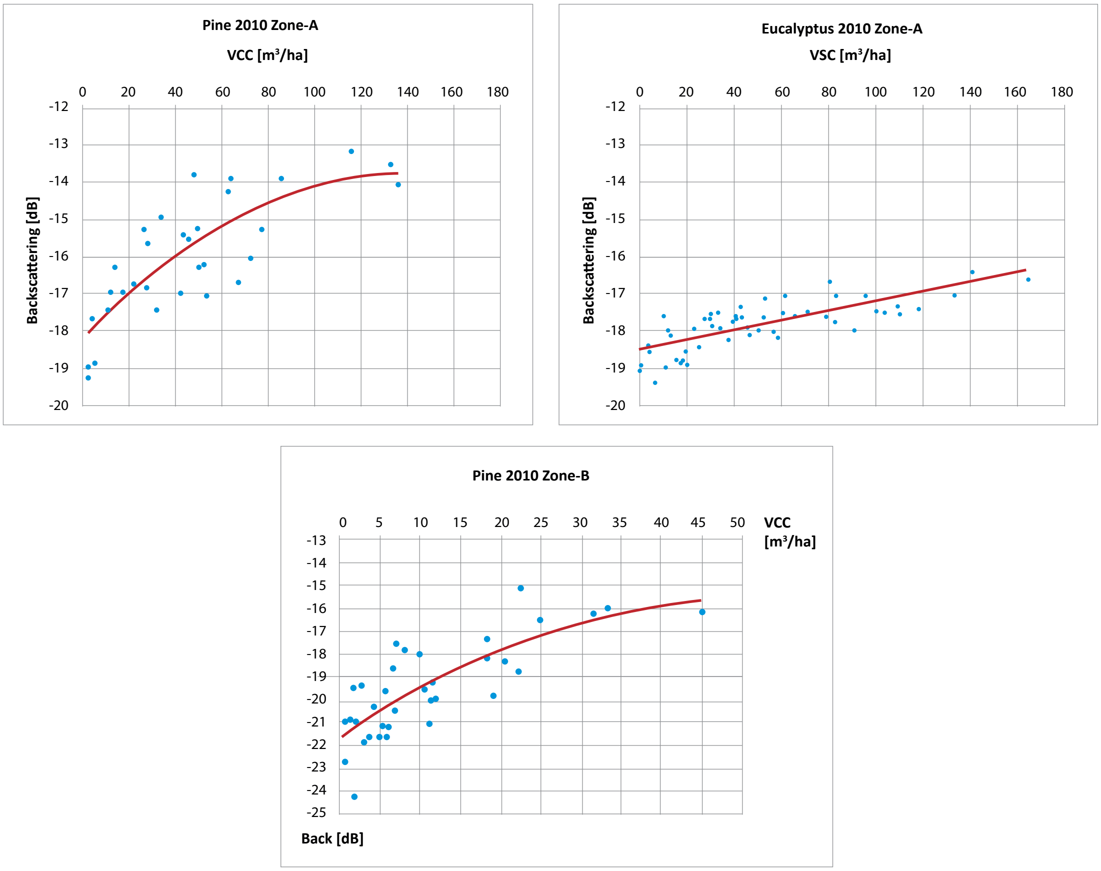

Figure 7. Training of models in 2010 for both zone, using the measured backscatter on HV cross-correlation images and the volume estimated from growth equations (point symbols). The trend of backscatter is represented by a line. VCC is the volume with bark; VSC is the volume without bark.

For both dates, the volumes for the remaining compartments in Zone-A and stands in Zone- B were estimated based on the resulting equations of inverting the models applied ([1] for WCM and [2] for the linear regression).

$$V = -\frac{1}{\beta}\ln\left(\left(\sigma^0_{veg} - \sigma^0_{for}\right)/\left(\sigma^0_{veg} - \sigma^0_{gr}\right)\right) \qquad [1]$$

$$V = \left(\sigma^0_{for} - ordinate\right)/slope \qquad [2]$$

Where, *V* represents the volume with bark for Pine trees and Holm oaks, and volume without bark for Eucalyptus trees (m^3/ha); σ^0_{for} represents the backscatter component from the canopy surface (decibels); σ^0_{veg} is the backscatter component of the internal vegetation structure (branches and trunks); σ^0_{gr} is the backscatter component from the ground; *β*, "*ordinate*" and "*slope*" are other coefficients obtained during the model training processes. The trained coefficients for each species, year and area ratio are shown in Table 2.

In order to validate the estimated volumes, the correlation coefficients, mean squared error per species in each area and year and relative RMSE were calculated. Table 3 summarizes the results achieved, to be discussed in the Results chapter.

Finally, allometric equations based on wood volume per unit area were used for calculating the aboveground biomass (Table 4). For Pine trees and Holm oaks, the equations employed are the ones listed in Vilén *et al.,* 2005, quoting Sabate *et al.,* 2005, while for Eucalyptus the equations listed in the Australian Government program "National Carbon Accounting System" (Polglase *et al.,* 1994), developed by the Australian Greenhouse Office, were used.

Table 2. Coefficients obtained in the models training. σ^0_{gr} and σ^0_{veg} are the components of the backscatter from ground and vegetation respectively; *β* is a coefficient obtained in the models training.

		PINE			EUCALYPTUS		HOLM OAK	
ZONE	YEAR	σ^0_{gr}	σ^0_{veg}	*β*	*Ordinate*	*Slope*	*Ordinate*	*Slope*
A	2008	-18.49090	-8.56744	0.00732	-18.76863	0.02295	--	--
	2010	-18.48580	-13.49090	0.01921	-18.39806	0.01124	--	--
B	2008	-21.64610	-13.93070	0.03919	Zone-A	Zone-A	-21.84600	0.22430
	2010	-21.71640	-14.31890	0.03861	Zone-A	Zone-A	--	--

Table 3. Validation table of models generated from pairs [backscatter, inventory volume] intended for this: correlation coefficient (R^2) and mean square error (RMSE). The average volume refers to the average volume estimated. (*) Observed saturation in backscatter for volumes greater than 100m^3/ha.

	SPECIES	YEAR	R^2	RMSE	Estimated average volume (m^3/ha)	Vol. Range in field (m^3/ha)
Zone-A	Pine	2008 (*)	0.75	15.06	37.82	3.40 – 125.10
		2010 (*)	0.87	18.93	45.18	3.80 – 135.50
	Eucalyptus	2008	0.66	21.29	45.14	3.19 – 146.58
		2010	0.73	46.71	90.58	5.30 – 199.95
Zone-B	Pine	2008	0.58	5.80	9.76	0.48 – 56.65
		2010	0.63	5.80	11.68	0.61 – 58.77
	Eucalyptus	2008	0.38	7.38	11.48	1.05 – 37.76
		2010	0.42	7.38	15.45	1.98 – 50.80
	Holm oak	2008	0.48	4.43	2.62	0.23 – 13.20

Table 4. Allometric equations. (VSC is the volume without bark; VCC is the volume with bark).

	DRY WEIGHT BIOMASS FRACTION (Tons/ha)		
SPECIES	TIMBER (BI_F)	BRANCHES (BI_R)	LEAVES (BI_H)
Eucalyptus	$\mathrm{BI\_WOOD} = 600\times\mathrm{VSC}$ $\mathrm{BI\_BARK} = 32\times(1-e^{-0.005\times\mathrm{BI\_WOOD}})$ $\mathrm{BI\_F} = \mathrm{BI\_WOOD}+\mathrm{BI\_BARK}$	$\mathrm{BI\_R} = 14.9\times(1-e^{-0.033\times\mathrm{BI\_F}})$	$\mathrm{BI\_H} = (16\times0.3\times\mathrm{BI\_F})/(16+0.3\times\mathrm{BI\_F})$
Pine	$\mathrm{BI\_F} = 0.46\times\mathrm{VCC}$	$\mathrm{BI\_R} = 0.16\times\mathrm{VCC}$	$\mathrm{BI\_H} = 0.035\times\mathrm{VCC}$
Holm oak	$\mathrm{BI\_F} = 0.69\times\mathrm{VCC}$	$\mathrm{BI\_R} = 0.37\times\mathrm{VCC}$	$\mathrm{BI\_H} = 0.049\times\mathrm{VCC}$

Figure 8 shows an area located in Zone-B which corresponds to the forest core “El Cobujón” mapping the results of dry aboveground biomass in tons/ha for 2008 and 2010.

4. Results and Discussion

After analyzing the validation of the results shown in Table 3, it is observed that the R^2 achieved in Pine trees is higher than in the other species and greater in Zone-A despite its difficult terrain. This is explained by Zone-A has young and mature forests, which results in an optimal sample data to train the models. Eucalyptus groves get worse results in both areas. In 2008, a R^2 of 0.66 for Zone-A is not a bad result, but it is very significant that it is only 0.38 for Zone-B. As discussed in the methodology chapter, data from Zone-B has been used to validate the empirical model fitted with data from Zone-A. The result indicates that the empirical model used to estimate volumes of eucalyptus requires a large sample of field data homogeneously distributed to move from a local to a regional scale. In Holm oaks results are bad. It is due to their low volume per hectare and its low density that make the surface scattering mechanism take precedence on the volume scattering mechanism.

Saturation of backscattering was obtained from 100 m^3/ha in pine for Zone-A in both years, a fact that was ahead in the introduction chapter. This is not detected for Zone-B as the range of stocks volume is lower, however, worse relationships are

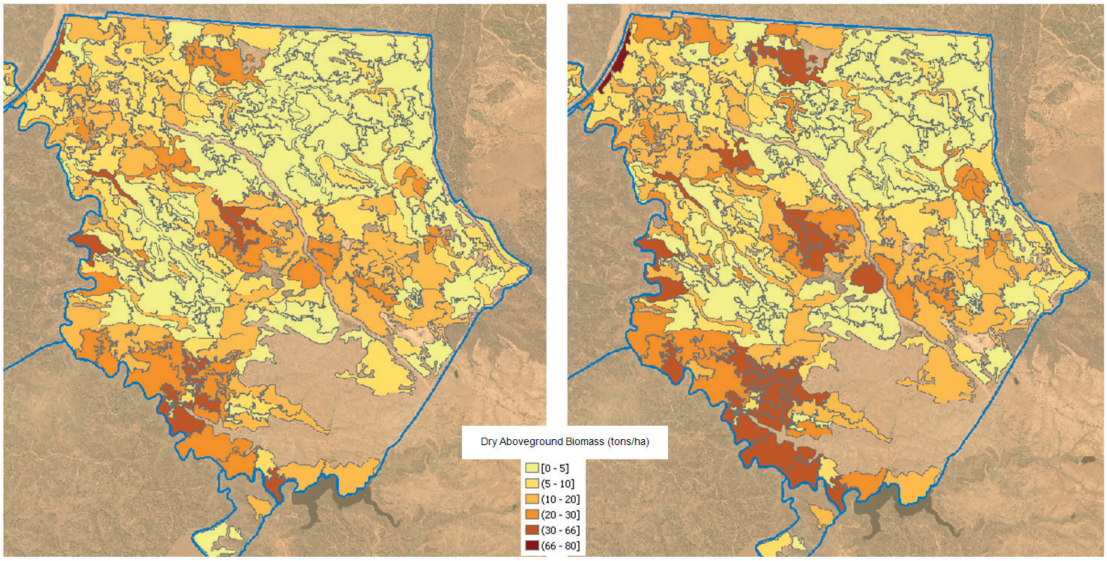

Figure 8. Dry aboveground biomass (tons/ha) obtained in an area of the forest core “El Cobujón” (Zone-B) in 2008 (left) and 2010 (right).

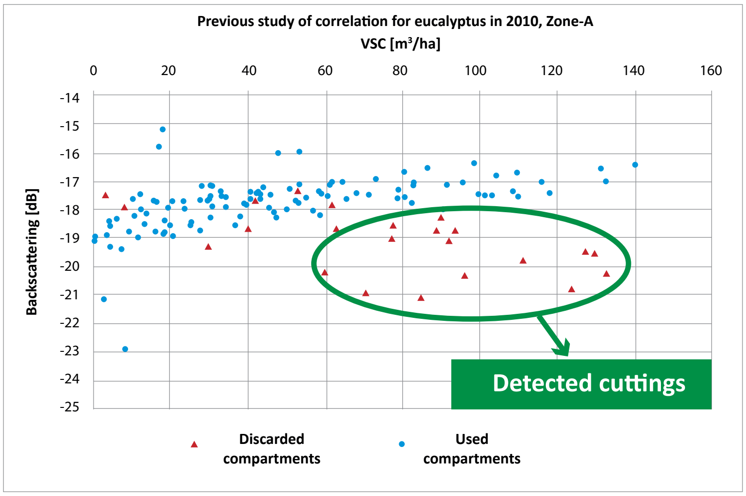

Figure 9. Correlation between backscatter and volume without bark (VSC) for eucalyptus compartments in Zone-A in 2010. Compartments with circular symbol mean those used in building model; with triangular symbol, discarded compartments.

obtained, so it could be said that volumes estimated with radar has not only saturation at high volumes but it is not good at low values (Tanase *et al.*, 2014). This seems what happened in eucalyptus, where saturation is not detected, but in both areas the results are worse. The use of the wavelength L (23 cm) has led to higher values of saturation than using shorter wavelengths as C. This limitation of SAR technology, arisen when using the backscatter coefficient for obtaining biomass, can be avoided with more advanced tools such as interferometry and/or polarimetric interferometry, which it is possible to obtain better estimates with (Treuhaft and Siqueira, 2004).

In the multi-temporal analysis, results in Zone-A have allowed to detect areas where differences of estimated volume (2010-2008) indicate a decrease in volume in 2010 in some compartments contrary to initial expectations. This difference has led to the detection of forestry activities (thinning, felling) held between the two dates (Figure 9), which has been corroborated by photo interpretation of these compartments on the PNOA orthophoto (Figure 10). The analysis and results could be more exhaustive, but there were just field data from 2008 and not from 2010, where field information has been estimated from growth equations.

In Zone-B it is not detected that the estimated volume in 2010 decreased considerably compared to 2008.

Because of great diversity of forest structures in Andalusia, it has required a model of each species, since a single curve fitting (or model “radar - forest mass”), i.e., a single set of coefficients, has been insufficient to account for the total aboveground biomass of the forest afterwards.

The choice of the two zones has been very useful to establish a methodological approach for a study at regional level. A different study unit was used in each zone (compartment in Zone-A and stand in Zone-B). It has been observed that the value of the backscatter, conditioned by land relief (terrain slopes), does not give real accounts of volume stocks (due to the existence of hidden areas not registered by the radar signal) and when extending the surface of study units the influence of this effect on the value of the backscatter is attenuated, since the influence of shaded areas generated by the relationship between radar observation angle (oblique to the ground) and terrain slope is minimized.

Considering applying this methodology to larger geographic areas, models would train at territorial entity level, being essential to have mapping derived from a Forest Management Plan or proceed to a segmentation from a homogeneous forest species mapping (e.g. SIOSE Andalusia 1: 10.000) for all area of interest. Several factors to consider: a previous analysis of the orography of study areas, an evaluation of field information (if available)

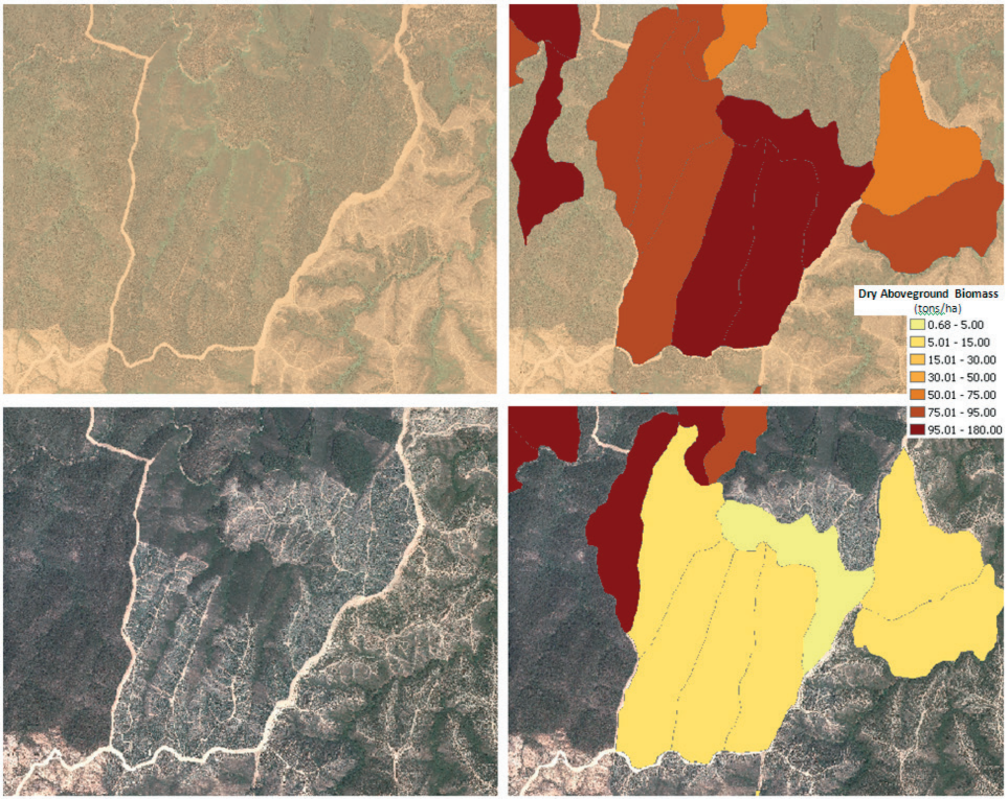

Figure 10. Dry aboveground biomass (tons/ha) in several compartments in Zone-A: up, PNOA orthophotography 2008-2009 (l.) and estimated biomass in 2008 (r.); down, PNOA orthophotography 2010-2011 (l.) and estimated biomass in 2010 (r.). It is observed forestry activity in 2010-2011 orthophoto and a corresponding decrease in biomass on this date.

and an analysis of distribution and behavior of species at regional level, as this may lead to the establishment of different numerical models of relationship between satellite imagery and ground truth in order to estimate the volume of forest masses properly. If necessary, in the absence of field data, a suitable field sampling is required.

Dependence on weather conditions for the image acquisition, the variability of the distribution of species and the topography of the area are relevant in the face of the need to carry out training of models for each date of analysis, even for the same species.

It is important to note the capacity of radar to detect thinning and felling at compartment level from registering a backscatter value (in 2010) that has dropped compared to the value the growth equations predict. A good interpretation of radar images can help identify areas where there have been these forestry activities.

Finally, the estimation based on direct observation of the territory through SAR remote sensing techniques can be an alternative solution to conventional methods, providing improvements in relation to the update rate and homogenous results in order to achieve an appropriate accuracy degree to regional management.

5. Conclusion

The areas under study, particularly Zone-A, have a significant topographical heterogeneity. Therefore it is essential to handle an accurate digital elevation model to correct the radiometry of the radar signal due to topographic effects in the orthorectification process.

It is very important to have a detail orthophotography/orthoimage from the dates of interest or very close to them. The PNOA orthophotography used in the project has a resolution of 0.5 m, but it has been resampled to 2.5 m for obtaining the forest mask and the stands segmentation in order to speed up the calculation process, which has been possible considering that the radar image is 15 m. This spatial resolution (2.5 m) would be equivalent to that of panchromatic SPOT satellite images, so depending on data availability latter could be used in place of orthophotos and even SPOT Multispectral (10 m). This availability of information is subject to the frequency or timing of updating images of PNOT: PNOA orthophotos coverage is provided every 3 years while an annual SPOT coverage is available under the PNT.

Having detailed images becomes necessary for the analysis of results through photo-interpretation.

In order to establish a methodological approach for future study at regional or subregional level, must be taken into account the need to have homogeneously distributed field information coming from a set of plots or forest management.

Models would be trained at territorial entity level (stand, compartment or territorial unit is considered). In case of no forest management plan from which stands or compartments resulting, segmentation can be generated, for what is important to have a mapping of species. In the case of Andalusia it is available SIOSE 1:10000. Orthophoto or SPOT image could also be used, preferably of the same year to avoid radar image decorrelations.

In the election of the territorial unit of study, prior analysis that evaluates the information field and the topography of the area is advised. In choosing training plots it is necessary to remember avoiding the error of the images georeferencing process or the GPS positioning errors. It is also important not to count plots that are on the edge of the compartment by the uncertainty generated, to prevent steep slopes, since the backscatter is too conditioned by the topography, and to avoid shadows areas regarding the vision sensor.

During training model, introducing entities which have evidence of irregular situations must be avoided, such as thinning or felling undertaken between the date of capture of field data and the date of acquiring the image.

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