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# The potential of multifrequency SAR images for estimating forest biomass in Mediterranean areas

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ABSTRACT

The extraction of forest information from SAR images is particularly complex in Mediterranean areas, since they are characterized by high spatial fragmentation and heterogeneity. We have investigated the use of multi-frequency SAR data from different sensors (ALOS/PALSAR and ENVISAT/ASAR) for estimating forest biomass in two test areas in Central Italy (San Rossore and Molise), where detailed in-situ measurements and Airborne Laser Scanning (ALS) data were available. The study focused on the estimation of growing stock volume (GS, in $m^3$/ha) by using an inversion algorithm based on artificial neural networks (ANN). The ANN algorithm was first appropriately trained using the available GS estimates obtained from ALS data. The potential of this algorithm was then improved through the innovative use of a simulated dataset, generated by a forward electromagnetic model based on the Radiative Transfer Theory (RTT). The algorithm is able to merge SAR data at L and C bands for predicting GS in diversified Mediterranean environments. The performed analyses indicated that GS was correctly estimated by integrating information from L and C bands on both test areas, with the following statistics: $R > 0.97$ and RMSE = 28.5 $m^3$/ha for the independent test, and $R = 0.86$ and RMSE ≈ 77 $m^3$/ha for the final independent validation, the latter performed on the forest stands of both areas not included in the ALS acquisitions and where conventional measurements were available. The research then illustrates the potential of using the obtained GS estimates from SAR data to drive the simulations of forest net primary production (NPP). This experiment produced spatially explicit estimates of GS current annual increments that are slightly less accurate than those obtained from ground observations ($R = 0.75$ and RMSE ≈ 1.5 $m^3$/ha/year).

## 1. Introduction

Forests and woodlands are the most widely distributed vegetation ecosystems on the planet, covering approximately 4000 million ha (FAO, 2015). The importance of forest monitoring is universally recognized, due to the role played by forests and other semi-natural ecosystems in provisioning a large number of different services and in acting as the main terrestrial carbon sink (Waring and Running, 2007). Today forest inventory programmes focus on the statistical assessment of numerous forest attributes. They have, in fact, evolved over the last decades from methods for estimating the forest productivity into global environmental survey programmes (Barbati et al., 2014). This generally leads to produce a constantly increasing amount of forest resource data; during the period from 1990 to 2014, 82% of the global forest area was included in at least one National Forest Inventory (NFI) (FAO, 2015). Historically NFIs have produced aggregated statistics over wide areas. However, wall-to-wall spatially explicit information (maps) on forest status and their related temporal dynamics obtained through the combined use of remotely sensed data is frequently requested today, especially in regions with scarce accessibility and limited ground data availability (McRoberts, 2008). Several applications can benefit from this spatial information: from the bioenergy production and sustainable forest management to the detection of land-use change and assessment of carbon stocks (Corona et al., 2002). This is particularly relevant considering the current decrease in forest resources; since 1990 > 3% of forest area has been lost (approximately 129 million of ha corresponding to 17.4 gigatonnes of forest biomass) especially in tropical regions (FAO, 2015).

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Several forest biophysical parameters (such as Leaf Area Index (LAI), aboveground biomass (AGB), and Net Primary Production (NPP)), which can be estimated through the combined use of remotely sensed images and field data, provide valuable information on the quantity, productivity and vegetative status of forest resources. What makes these parameters so significant is that they are strictly related to the amount of carbon stocked, which is a relevant information within the global carbon cycle (Pierce and Running, 1988).

In view of these considerations, the possibility to estimate forest biomass from both active and passive remote sensing observations gathered from satellite and/or aircraft platforms is undoubtedly appealing. Passive optical sensors have been widely used at different ground resolutions, although these sensors can only detect the upper layer of the canopy and operate in clear-sky conditions (e.g. Tucker, 1979; Guyot et al., 1989). This makes the investigation of equatorial, boreal, and mountain areas rather difficult due to the frequent and consistent cloud cover.

A promising remote sensing technique for forest applications is based on visible/infrared active sensors (LiDAR, Light Detection and Ranging), which have been used increasingly for both detecting individual tree characteristics and producing wall-to-wall spatially explicit estimations of forest variables (Sun and Ranson, 2000; Packalén and Maltamo, 2008; Bottai et al., 2013). LiDAR (which is a component of the ALS - Airborne Laser Scanning) has been so far operated by aircrafts only, making it costly and of limited scope, as the spatial extents of each area investigated are relatively small (Montaghi et al., 2013). The irregular acquisitions carried out by using ALS also depend on the national budgets and priorities. The only satellite with a LiDAR system onboard was the ICESat satellite, which was able to acquire large footprint information suitable for continental applications (Boudreau et al., 2008). The second generation of the laser altimeter ICESat-2 is scheduled for launch in 2017.

Thanks to their independence from cloud cover and solar radiation and their significant penetration through vegetation, microwave frequencies have proven to be a suitable spectral band for forest investigations (Ulaby et al., 1990). This became particularly evident especially after the launch of new satellites which have synthetic aperture radar (SAR) sensors onboard and obtain images at very high spatial resolution and very frequent revisit time (e.g. Cosmo-SkyMed, TerraSAR-X, and Sentinel-1). In the microwave region, dielectric characteristics of vegetation material are considerably influenced by both moisture content and geometrical features of plant constituents (e.g. stems, branches, and leaves). These factors affect scattering differently and to a different extent according to frequency and polarization (Ferrazzoli and Guerriero, 1995). Experimental and theoretical investigations carried out over many years have shown that microwave backscattering at various frequencies and polarizations is sensitive to forest characteristics, thus allowing the identification of forest/non forest areas and forest thermal state (frozen/thawed). Moreover, the ability of SAR data in estimating several parameters including forest density, tree height and above ground biomass or stem volume was confirmed (e.g. Le Toan et al., 1989; Ulaby and Dobson, 1989; Wang et al. 1994 and 1995; Ferrazzoli et al., 1997; Paloscia et al., 1999; Kasischke et al., 1997; Ackermann et al., 2012; Kaasalainen et al., 2015; Baghdadi et al., 2015).

The total backscatter from a forest is a combination of the backscatter from ground and vegetation where radiation is scattered by stems, branches, twigs, leaves or needles. Ulaby et al. (1990) identified eleven components of radar backscatter of tree canopies, considering direct and diffuse scattering from ground and various vegetation components, as well as their interactions. The importance of each component on the total scattering mostly depends on the microwave wavelength. In case of a dense canopy, at wavelengths shorter than 10 cm (e.g. C (6 cm) and X (3 cm) bands), information originates from the first layers of vegetation, since the backscatter is mainly due to smaller tree elements (leaves or needles and small branches of the upper crowns), understory layers and soil surface with a low influence in the total scattering. By using these frequencies a sharp discrimination between clear-cut and forest stands can thus be obtained (Hoekman, 1993; Mougin et al., 1993; Wang et al., 1994; Paloscia et al., 1999; Grover et al., 1999).

Radiation penetrates more deeply into the observed surfaces at longer wavelengths, i.e. L (between 21 and 24 cm) and P bands (about 67 cm), than at shorter ones, and the backscatter mainly originates from interactions with branches, trunks and ground beneath the canopy, whereas the twig and leaf contribution is negligible (Richards et al., 1987; Le Toan et al., 1992). As discussed in Woodhouse et al. (2012), these interactions also implicate that the backscattering is strongly affected by the forest structure as well as its spatial variability (Saatchi et al., 2011). L and P bands are consequently the most suitable frequencies for estimating forest biomass (Le Toan et al., 1992; Ranson and Sun, 1994; Dobson et al., 1992; Rignot, 1996; Ahmed et al., 2014; Hensley et al., 2014). At L band, the relationship between the backscattering coefficient ($\sigma°$) and Growing Stock volume (GS, $m^3$/ha) has a logarithmic shape, showing a saturation of radar backscatter at values of woody volume from less than 200 $m^3$/ha (Ferrazzoli and Guerriero, 1995) up to 400 $m^3$/ha (mainly in HV polarization) in Mediterranean forests, according to the experiments carried out by Italian research groups (Ferrazzoli et al., 1997; Paloscia et al., 1999).

The incoming BIOMASS ESA mission, a P band spaceborne SAR, will overcome the problem of signal saturation at L band for high forest biomass (Le Toan et al., 2011). However, since this mission's scientific results are awaited, the available multi-frequency and multi-polarization satellite data can provide useful information on other forest characteristics, which are transparent at longer wavelengths.

Past research has been conducted over a wide range of climatic zones using both satellite and airborne SAR systems; however, most investigations mainly focused on the boreal forests of North America and Eurasia and, in some cases, on more temperate coniferous forests, based on their influence on climate changes (Dobson et al., 1992; Ranson and Sun, 1994; Antropov et al., 2013), as well as in tropical regions due to the frequent cloud cover (Santos et al., 2003; Rignot, 1996; Mitchard et al., 2012). More recent works have also been devoted to investigating Mediterranean forests, although they are mostly devoted to the study of forest fire events and the successive re-growth of biomass (e.g. Minchella et al., 2009; Tanase et al., 2011).

These investigations indicated that, in general, the estimate of major forest features (type, above ground biomass, growing stock, etc.) from SAR data is not an easy task. Moreover, Mediterranean forests offer increasingly complex retrievals, as they are characterized by much higher spatial fragmentation and heterogeneity than other forest types (Dafis, 1997). These forests have been shaped by an intensive anthropogenic pressure (for forest lodgings, urbanization and agriculture) since the development of the first human societies. The irregular orography of Mediterranean areas contributes in creating steep gradients of ecological variables in very short geographical distances and rich biological diversity (Scarascia-Mugnozza et al., 2000). The variable aridity conditions typical of the Mediterranean climate represent an additional perturbing factor, since they irregularly limit foliage density, producing incomplete and discontinuous plant canopies. This high spatial complexity increases the cost of traditional field based forest inventories and more generally complicates the applicability of all mapping and monitoring methods. On the other hand, the great environmental value of Mediterranean forests, joint to their high vulnerability to human induced disturbances and climate changes (Penuelas et al., 2002), enhances the need for intense monitoring programs.

The use of SAR data is therefore expected to be particularly challenging and rewarding in Mediterranean areas. This situation provides the fundamental motivation for the current research, which aims at assessing the sensitivity of multi-frequency SAR data to forest characteristics and exploiting the SAR backscatter capabilities for estimating GS in Mediterranean areas.