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Estimation of aboveground biomass in Mediterranean forests by statistical modelling of ASTER fraction images

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ABSTRACT

Aboveground biomass (AGB) estimation from optical satellite data is usually based on regression models of original or synthetic bands. To overcome the poor relation between AGB and spectral bands due to mixed-pixels when a medium spatial resolution sensor is considered, we propose to base the AGB estimation on fraction images from Linear Spectral Mixture Analysis (LSMA). Our study area is a managed Mediterranean pine woodland (*Pinus pinaster* Ait.) in central Spain. A total of 1033 circular field plots were used to estimate AGB from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) optical data. We applied Pearson correlation statistics and stepwise multiple regression to identify suitable predictors from the set of variables of original bands, fraction imagery, Normalized Difference Vegetation Index and Tasselled Cap components. Four linear models and one nonlinear model were tested. A linear combination of ASTER band 2 (red, 0.630–0.690 μm), band 8 (short wave infrared 5, 2.295–2.365 μm) and green vegetation fraction (from LSMA) was the best AGB predictor ($R^2_{adj} = 0.632$, the root-mean-squared error of estimated AGB was 13.3 Mg ha^{-1} (or 37.7%), resulting from cross-validation), rather than other combinations of the above cited independent variables. Results indicated that using ASTER fraction images in regression models improves the AGB estimation in Mediterranean pine forests. The spatial distribution of the estimated AGB, based on a multiple linear regression model, may be used as baseline information for forest managers in future studies, such as quantifying the regional carbon budget, fuel accumulation or monitoring of management practices.

1. Introduction

Information about aboveground biomass (AGB) has in recent years become a goal for inclusion in forest management, given the increasing interest of industrial, energy and environmental sectors. The potential of forests as a biomass source for yielding clean energy and as carbon sinks makes it a frequent issue in regional and county level studies (Zheng et al., 2004; Gallaun et al., 2010). Accurate estimation of biomass is fundamental for assessing the role of forests in the global carbon cycle, particularly when defining their contribution towards sequestering carbon (Popescu, 2007; Zolkos et al., 2013).

Forest inventory data often provide the base data required to enable large area mapping of biomass over a range of scales, whereby measurements of tree size and stand structure, along with statistical models, are used in estimating tree and stand biomass (Fazakas et al., 1999). According to the International Panel on Climate Change Good Practice Guidance (IPCC CPG, 2003), remote sensing techniques are useful for verifying Land Use and Land cover (LULC) and LULC changes, carbon estimation and, especially, forest AGB in the Kyoto protocol context. Specifically, remote sensing has been considered a relatively fast, reliable and cost-effective approach in forest inventory and mapping by means of the correlation of parameters such as tree density, basal area, volume, biomass, and so forth, with the reflectance values recorded in satellite images (Kwak et al., 2007; Blackard et al., 2008).

AGB is usually estimated from remote sensed data via a direct relationship between the spectral response (original or transformed sensor bands) and AGB. In this sense, the Normalized Difference Vegetation Index (NDVI) is the most commonly used vegetation index (e.g. Zheng et al., 2004; Soenen et al., 2010; Ji et al., 2012; Poulain et al., 2012). Linear transformation of multiple bands, such as Tasselled Cap (TC) transform, has been also utilized as

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variable in regression models for estimating forest parameters (e.g. Phua and Saito, 2003; Lu et al., 2004; Hall et al., 2006). Some authors have focused on multiple regression analysis techniques (e.g. Dong et al., 2003; Ji et al., 2012; Ghasemi et al., 2013); some, on non-parametric *k*-nearest neighbour techniques (*k*-NN) (e.g. Labrecque et al., 2006; Fuchs et al., 2009) or on artificial neural networks (ANN) (e.g. Foody et al., 2001). Other works used indirect relationships whereby attributes estimated from canopy parameters, such as crown diameter, are first derived from remotely sensed data using multiple regression analysis of different canopy reflectance models (e.g. Phua and Saito, 2003; Soenen et al., 2010). Previous literature, however, has indicated that multiple regression analysis may be the most common approach for development of AGB estimation models, especially when medium spatial resolution data are used (Lu, 2006).

Remote sensing studies (e.g. Elmore et al., 2000; Ji et al., 2012; Tian et al., 2012; Gao et al., 2013; Main-Knorn et al., 2013; Barbosa et al., 2014;) have estimated AGB using both active and passive sensors in a broad range of scales (global, regional and local), although optical satellite data (particularly data from Landsat sensors) is often used. The limitation in spatial, spectral and radiometric resolution inherent in the optical remotely sensed data is an important factor affecting the AGB estimation performance (Lu, 2006). A problem typically observed in forests when using a coarse or medium resolution sensor like Landsat ETM+ (30-m spatial resolution) is the 'mixed pixel' condition (Asner, 1998). The combined reflectance observed is not only due to the amount of vegetation present, but also to other factors such as soil or shadow (Davidson and Csillag, 2001). The relation between AGB and vegetation indices or spectral bands may be poor because of this effect.

Spectral mixture analysis (SMA) is a frequently used subpixel-method to reduce the mixed-pixel problem (e.g. Lewis et al., 2012; Kuusinena et al., 2013). It unmixes a multispectral image into fraction images that represent the areal proportion of each endmember (e.g. vegetation abundance, soil and other spectrally distinct materials that basically contribute to the spectral signal of mixed pixels) in a pixel (Lu, 2006; Quintano et al., 2012). In remote sensing data applications, SMA has been used extensively in past studies for determining urban vegetation abundance (e.g. Demarchi et al., 2012; Michishita et al., 2012; Deng and Wu, 2013), estimating biophysical parameters such as leaf area index, biomass and net primary productivity (e.g. Zheng et al., 2004; Wang and Qi, 2008; Huang et al., 2009), mapping burned areas (Quintano et al., 2006, 2013; Fernández-Manso et al., 2009) or mapping surface coal affected areas (Fernández-Manso et al., 2012). Regarding AGB, previous studies (e.g. Peddle et al., 2001; Soenen et al., 2010; Morel et al., 2012) showed the superiority of fraction images derived from SMA compared to original bands or vegetation indices to estimate biomass from medium spatial resolution imagery.

Most AGB studies have been carried out in uniform boreal forests of coniferous plantations (Häme et al., 1997; Muukkonen and Heiskanen, 2005) and temperate and tropical forests (Phua and Saito, 2003; Cutler et al., 2012). There is a lack of experience for estimating AGB in Mediterranean environments (Salvador and Pons, 1998). However, the study of Sevillano-Marco et al. (2013) can be mentioned. They estimated AGB from the Chinese-Brazilian Earth Resources Satellite (CBERS) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data in *Pinus radiata* D. Don in Spain.

In this sense, our study is innovative. It estimates AGB in Mediterranean ecosystems where Mallinis et al., 2004 found that Landsat TM spatial resolution did not seem to be adequate, given the patchy and fragmented spatial pattern of forest resources. To overcome such limitations, we use ASTER data whose three first bands (VNIR) have a higher spatial resolution than Landsat data (15 m vs. 30 m) and let us artificially extend such spatial resolution to the rest of short wave infrared (SWIR) bands by means of a spectral sharpening algorithm (Welch and Ahlers, 1987). In addition, to minimize the mixed-pixel problem (which still occurs at 15 m spatial resolution), we propose to use fraction images from LSMA to improve the AGB estimation. The study will determine which ASTER spectral band, fraction imagery, NDVI and/or TC component show a good statistical relation with AGB. Multiple regression analysis will help us to develop AGB estimation models. The spatial distribution of the estimated AGB from spectral data may help forest managers and the not, as yet, established biomass market that could be an alternative to the decline being suffered by traditional productive uses (timber and resin tapping).

2. Materials and methods

2.1. Study area

The study site is located in the area known as 'Tierra de Pinares Segoviana', in the Southeast of Castilla y León, province of Segovia (Fig. 1). It lies on sandy materials composed mainly of quartz grains over Miocenic materials. The terrain is a peneplain with low relief and a general, gentle slope from the southeast to northeast with a range of elevations 750–900 m above sea level. Mediterranean pine (*Pinus pinaster* Ait.) is the only vegetation type in our study area, that is the centre of a surface of approximately 20 000 ha of a monospecific pine forest. Currently, floristic composition and vegetation structure is a consequence of an anthropic management of over a hundred years.

Specifically, the study area corresponds to a public forest in the province of Segovia, 6850 ha in extent. The forest performs an important role against erosion and, no less important, in mitigating climate change. In recent years, it has gained importance for the use of biomass from both shelterwood cuttings and waste produced from silvicultural treatments. It has been managed by a Forest Management Plan since 1912 with the main goals of yielding resin and timber, generating the landscape, biodiversity and recreational areas. The forest was delineated to management compartments (photointerpretation and field work) by the Regional Forest Board. The forest compartment is the smallest unit for which decision-supporting information is collected and stored and it consists of a homogeneous forest in terms of tree species and age classes. Compartment size was in the range of 13.3–61.8 ha (mean = 33.2 ha, standard deviation = 10.6 ha). The borderlines of the compartments can be seen in Fig. 1.

2.2. Materials

Field data was acquired from an intensively sampled local test area with 1 033 circular sample plots (r = 16 m), which were allocated in a 200 m-quadratic grid. A field survey was conducted between May and July, 2001. Field measurements included the diameter at breast height (DBH) of each tree with a DBH over 10 cm, which was measured to the nearest 0.1 cm with digital callipers. Total height was measured to the nearest 0.1 m with a digital hypsometer (Vertex III) in two trees of each plot (closest trees to the plot centre oriented to the north and south).

We used an ASTER level L1B image (radiometric calibrated and co-registered data on all image channels), recorded on 6 June 2001 to estimate the AGB.

2.3. Methods

Fig. 2 shows the steps followed to estimate AGB from ASTER optical data. First, we calculated the AGB within each plot from the DBH measured in the field. Second, the ASTER data was pre-processed and then NDVI and TC components were calculated.