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Mapping stand volumes of *Pinus halepensis* Mill in a semi-arid region using satellite imagery of the Sénalba Chergui forest in north-central Algeria

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ABSTRACT

We developed an approach using remote sensing and modeling, applicable to Algerian forest inventory, for estimating the volume of timber in Aleppo pine stands. We used ordinary linear regression (OLR) and reduced major axis (RMA) regression to assess an operational model to map stand volume from satellite images. Our analysis was supported by measurements from 151 sample plots and spectral values from remote sensing imagery. Fifteen candidate models were tested through the Akaike Information Criterion to assess their predictive power. For the 2009 Landsat TM image, we found that the best models for both regression methods used the NDVI as the independent variable. The RMSEs were 20.3% (16.10 m^3 ha^{-1}) and 22.5% (17.83 m^3 ha^{-1}), respectively, for OLR and RMA. We chose the RMA regression models because they had realistic standard deviation values for the estimated volumes, and they gave lower RMSEs in volume classes over 40 m^3 ha^{-1}. Our method gave similar results for two other images, which demonstrated that our approach was robust when applied to data from a different year (2006 Landsat TM), but from the same sensor, and also to data from a different sensor (2005 Alsat-1).

1. Introduction

Mapping forest variables like stand volumes is fundamental for forest planning and management. A comprehensive and accurate inventory is needed to support sustainable forest management for conservation and production, to fulfill the monitoring required by the Food and Agriculture Organization of the United Nations (FAO), and to implement the United Nations Framework Convention on Climate Change (UNFCCC) of which Algeria has been a party since 1993. Estimation of wood volume and biomass are key variables to establish a link between carbon exchange between forest and atmosphere (Schroeder et al., 1997).

There is a pressing need to update national and regional forest inventories in Algeria, where the last traditional forest inventory was conducted in 1984. The national forested area is approximately 4.7 million hectares (ha); about 1.2 million ha of this area is of economic importance to the forest industry (DGF, 2007). The national forest inventory published in 1984 estimated the national standing wood volume at 55 million m^3 with an annual increment of about 1.6 million m^3. The portion estimated to be *Pinus halepensis* Mill. (Aleppo pine) was 30 million m^3 with an annual increment of about 1.2 million m^3 (DGF, 2007).

Remote sensing methods have been developed to overcome the limitations of traditional inventory techniques, and they have led to a growing variety of inventory data and derivative products (McRoberts and Tomppo, 2007). Since the first Landsat carrying a Multispectral Scanner System (MSS) was launched in 1972, remote sensing and various modeling methods have been used in forest inventory studies: regression analysis (Ardö, 1992; Gasparri et al., 2010; Lu, 2005; Salvador and Pons, 1998; West, 1995); k-nearest neighbor method (Franco-Lopez et al., 2001; McRoberts and Tomppo, 2007; Mäkelä and Pekkarinen, 2004; Tomppo et al., 2008); neural networks (Foody et al., 2003); and fuzzy logic (Triepke et al., 2008). Remote sensing data, geographic information systems, and modeling are now often used in ecological studies (Cohen and Goward, 2004). According to McRoberts and Tomppo (2007), remote sensing data improve forest inventories in the following ways: (1) availability of easily acquired geospatial data at lower cost than aerial photography; (2) inventories for large areas that are more accurate, often through stratified and weighted estimates; (3) estimates of smaller areas where field data are

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unavailable; and (4) production of thematic maps of forests that can be used for ecological studies and timber production and supply.

Besides directly using the spectral bands of satellite sensors, vegetation indices and tasseled cap transformations are frequently used to link spectral information to forest parameters by developing direct relationships (Cohen et al., 2001; Powell et al., 2010). The normalized difference vegetation index (NDVI) is widely used to obtain information about vegetation (e.g., forest cover) from remote sensing data (Foody et al., 2003), particularly for covers with a leaf area index (LAI) of 3 or less. Tasseled cap indices are often used in vegetation mapping and monitoring applications: estimating forest age and structure (Cohen et al., 1995); estimating and mapping wood density and volume (Franco-Lopez et al., 2001); modeling forest cover attributes (Cohen et al., 2001); mapping forest disturbances (Healey et al., 2005); and estimating biomass (Powell et al., 2010). Most forest mapping methods involved the development of empirical relationships between the spectral data of satellite images and stand attributes as measured in sample plots (Franklin, 1986; Puhr and Donoghue, 2000; Foody et al., 2003). For example, Cohen and Spies (1992) obtained strong correlation ($R^2 > 0.74$) between the wetness component of the tasseled cap and the diameter at breast height and tree density. When developing new methods for forest mapping, it is important to consider how spectral values or indices might be useful for assessing forest parameters.

Mapping structural variables of forest ecosystems in semi-arid and savanna regions using satellite remote sensing has been investigated by Franklin and Hiernaux (1991), Larsson (1993) and Gasparri et al. (2010). Here, our objective was to develop methods applicable to Algerian forest inventory for mapping the total wood volume in forest stands of Aleppo pine. The work aimed at developing a procedure more cost-effective than traditional forest inventory methods, using remote sensing to produce maps of the average wood volume expressed in cubic meters per hectare (m^3 ha^{-1}) for each forest pixel. The proposed method was also tested for different acquisition years and for two different sensors (Landsat and Alsat-1) to assess how the models change over time and across sensors.

2. Materials and methods

2.1. Study area

The Sénalba Chergui natural forest (36°36′ N–36°42′ N, 3° E–3°12′ E) is 3 km northwest of the city of Djelfa in the central region of the Ouled Nail mountain range in the Saharan Atlas (Fig. 1). The range runs from southwest to northeast with a maximum elevation lower than 1300 m. The low relief landscape is due to its lithological homogeneity (marly limestone) (BNEF, 1984a). The pedogenic features that characterize Sénalba soils are primarily limestone accumulations, shallow depths, and significant moisture deficits (Halitim, 1988). The region's forest formations belong to the Mediterranean stage of vegetation in semi-arid areas where annual precipitation ranges from 300 to 400 mm (Chakali, 2007). Two contrasted seasons take place, one cooler with more rain and the second very dry with warm and hot temperature. Maximum mean daily temperature is 34 °C in July and minimum mean daily temperature is next to 0 °C in January.

The forest area in our study covered 17,562 ha. Most forest stands were composed essentially of only one species, Aleppo pine. Understory, often degraded from anthropological pressures, were composed, in order of dominance, by *Quercus ilex* L. (holm oak), *Juniperus phoenicea* L. (Phoenician juniper), and *Juniperus oxycedrus* L. (prickly juniper). The herbaceous layer was comprised of *Rosmarinus officinalis* L. (rosemary), *Globularia alypum* L. (globularia), *Stipa tenacissima* L. (alfa), and *Cistus libanotis* L. (rockrose). The main land cover categories for the study area were young and mature stands of Aleppo pine, and cypress and shrubland with or without trees. The forest included in our study area is under a conservation program although there might be some illegal cutting and settlements. The only available forest inventory for the study area dates from 1984. It describes fairly poor volumes (assessed as wood volume ranging from 11 to 54 m^3 ha^{-1}) of mature stands of Aleppo pine with an average of 45 m^3 ha^1 and an annual increase of 1.8 m^3 ha^{-1} (BNEF, 1984b). Representing the last natural barrier to desert encroachment, this area is also subject to climatic and edaphic constraints that impede the natural regeneration process.

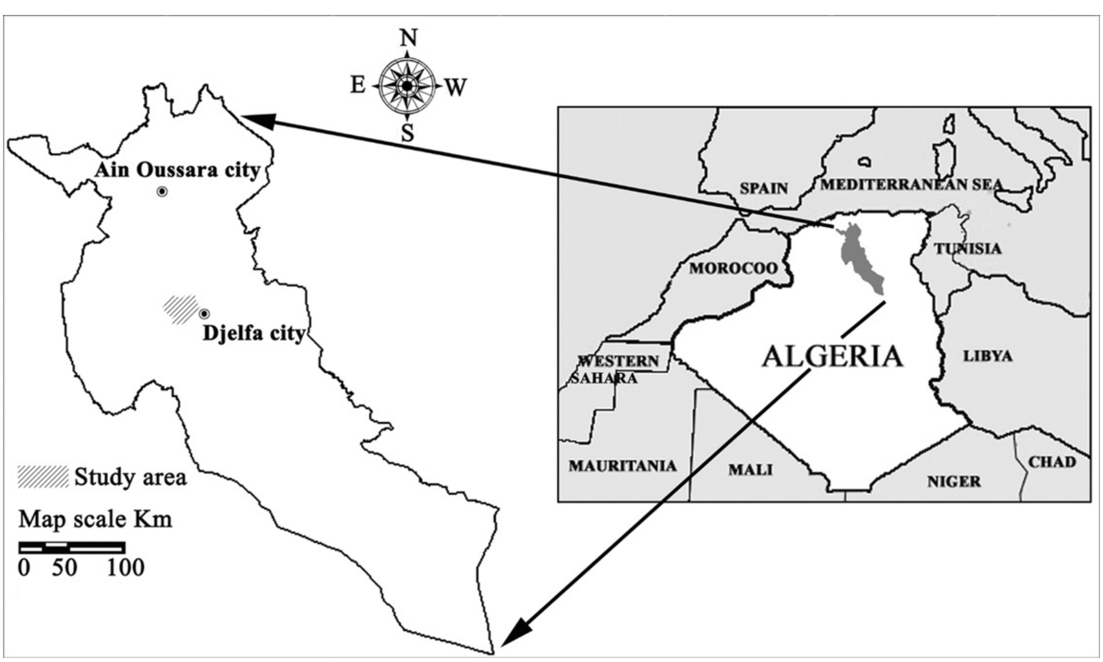

Fig. 1. Location of the study area in the Sénalba Chergui natural forest of north-central Algeria.