International Journal of Applied Earth Observation and Geoinformation 57 (2017) 145–153

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

journal homepage: www.elsevier.com/locate/jag

Modeling Mediterranean forest structure using airborne laser scanning data

Francesca Bottalico[a], Gherardo Chirici[a], Raffaello Giannini[a], Salvatore Mele[b], Matteo Mura[a], Michele Puxeddu[b], Ronald E. McRoberts[c], Ruben Valbuena[d,e], Davide Travaglini[a,*]

[a] Dipartimento di Gestione dei Sistemi Agrari Alimentari e Forestali, Università degli Studi di Firenze, via San Bonaventura 13, 50145 Florence, Italy
[b] Ente Foreste della Sardegna, Viale Luigi Merello 86, 09123 Cagliari, Italy
[c] Northern Research Station, U.S. Forest Service, Saint Paul, MN 55108, USA
[d] University of Eastern Finland, School of Forest Sciences, Yliopistokatu 7, FI-80100 Joensuu, Finland
[e] European Forest Institute HQ, Yliopistokatu 6, FI-80100 Joensuu, Finland

ARTICLE INFO

Article history:
Received 12 May 2016
Received in revised form 7 October 2016
Accepted 19 December 2016
Available online 5 January 2017

Keywords:
Forest biodiversity
Forest inventory
Forest monitoring
Structural complexity indicators
Airborne laser scanning
LiDAR

ABSTRACT

The conservation of biological diversity is recognized as a fundamental component of sustainable development, and forests contribute greatly to its preservation. Structural complexity increases the potential biological diversity of a forest by creating multiple niches that can host a wide variety of species. To facilitate greater understanding of the contributions of forest structure to forest biological diversity, we modeled relationships between 14 forest structure variables and airborne laser scanning (ALS) data for two Italian study areas representing two common Mediterranean forests, conifer plantations and coppice oaks subjected to irregular intervals of unplanned and non-standard silvicultural interventions. The objectives were twofold: (i) to compare model prediction accuracies when using two types of ALS metrics, echo-based metrics and canopy height model (CHM)-based metrics, and (ii) to construct inferences in the form of confidence intervals for large area structural complexity parameters.

Our results showed that the effects of the two study areas on accuracies were greater than the effects of the two types of ALS metrics. In particular, accuracies were less for the more complex study area in terms of species composition and forest structure. However, accuracies achieved using the echo-based metrics were only slightly greater than when using the CHM-based metrics, thus demonstrating that both options yield reliable and comparable results. Accuracies were greatest for dominant height (Hd) (R^2 = 0.91; RMSE% = 8.2%) and mean height weighted by basal area (R^2 = 0.83; RMSE% = 10.5%) when using the echo-based metrics, 99th percentile of the echo height distribution and interquantile distance. For the forested area, the generalized regression (GREG) estimate of mean Hd was similar to the simple random sampling (SRS) estimate, 15.5 m for GREG and 16.2 m SRS. Further, the GREG estimator with standard error of 0.10 m was considerable more precise than the SRS estimator with standard error of 0.69 m.

1. Introduction

Biological diversity is currently recognized as one of the pillars of sustainable development (UNCBD, 1992), and forests, which cover almost one-third of the globe, contribute greatly to preserving this biological richness (FAO, 2015). In this context, techniques and tools for assessing and monitoring the status of biodiversity at the global scale, or even for relatively large areas, are of undoubted value. Remotely sensed data assist in this effort by offering the possibility of synoptic views across large areas (Nagendra, 2001; Turner et al., 2003; Nagendra et al., 2013). Although biodiversity is frequently expressed in terms of species diversity, structural complexity is one of the most straightforward indicators of potential biodiversity and habitat suitability for woodlands (Winter et al., 2008; Chirici et al., 2011, 2012). Structurally diverse forest stands with vertical canopy layering and a variety of tree diameters provide a greater mix of potential habitats for birds, mammals, insects and microorganisms and, therefore, contribute more to preserving biodiversity (McElhinny et al., 2005). In addition, the importance of structure

* Corresponding author.
E-mail addresses: matteo.mura@unifi.it (M. Mura), davide.travaglini@unifi.it (D. Travaglini).

http://dx.doi.org/10.1016/j.jag.2016.12.013
0303-2434/

in contributing to the preservation of forest biological diversity is recognized at international levels (MCPFE, 2011) and has been demonstrated in multiple studies (Lähde et al., 1999; Puumalainen et al., 2003; Kuuluvainen, 2009).

Multiple variables can be used to quantify forest structure. Common forest inventory variables such as tree diameters and tree heights are often used (Franklin et al., 1981; Acker et al., 1998; Zenner, 2000; Lexerød and Eid, 2006) as is growing stock volume (Kuuluvainen et al., 1998; Uotila et al., 2002) which is often used to define old-growth (Wirth et al., 2009) and high nature value forests (European Environmental Agency, 2012). In addition, a variety of structural complexity indices have been tested and reported in the literature for assessing habitat functions (Neumann and Starlinger, 2001) and for forest management planning (Pommerening, 2002). The most commonly used structural complexity indices are based on tree diameters, heights, or both (Staudhammer and LeMay, 2001; Müller and Vierling, 2014) with indices based on diameter of particular relevance for forest management purposes (Lexerød and Eid, 2006; Valbuena et al., 2013).

Latifi (2011) exploited the potential of remotely sensed data as a source of auxiliary information for predicting forest structure, finding that airborne laser scanning (ALS) data outperform other sources of remotely sensed data. ALS data have been used successfully to predict and analyze forest structure (Evans et al., 2009; Lefsky et al., 2002; Lim et al., 2003; Zimble et al., 2003; Wulder et al., 2008; Valbuena et al., 2014; Mura et al., 2015, 2016). Further, ALS data have been used effectively for habitat modelling (Simonson et al., 2014; Vihervaara et al., 2015) for taxa such as terrestrial birds (Graf et al., 2009), beetles (Müller and Brandl, 2009), spiders (Vierling et al., 2011), and mammals such as bats (Jung et al., 2012), deer (Ewald et al., 2014) and squirrels (Nelson et al., 2005). However, few studies (Mura et al., 2015; Valbuena, 2015) have focused specifically on predicting Mediterranean diameter- and height-based forest structure variables using ALS data, or have assessed the implications for biodiversity.

Information extracted from ALS pulse return heights is commonly formulated into metrics that serve to describe and quantify the distributions of those heights. Two main classes of metrics are extracted from ALS data for use as covariates with predictive models: (i) echo-based metrics, and (ii) canopy height model (CHM)-based metrics (Popescu and Hauglin, 2014). Echo-based metrics are statistics extracted directly from the ALS point cloud and require access to the raw ALS data, usually in native ".LAS" format (ASPRS, 2013). However, ALS data acquired for other purposes are often not available for forestry applications with the result that calculation of echo-based metrics from the raw data necessary is not possible (Montaghi et al., 2013). Instead, interpolations of the raw ALS echo heights are often available in the form of two gridded raster layers: ground heights for all pixels characterized as a digital elevation model (DEM) and absolute heights for all pixels characterized as a digital surface model (DSM). A CHM is constructed by calculating pixel-by-pixel differences between the DSM and the DEM (Kraus and Pfeifer, 1998) and represents the top canopy height for each pixel. A CHM is the main layer used for forestry applications when raw ALS data are not available.

The objectives of the study were twofold: (i) to compare model prediction accuracies when using two types of ALS metrics, echo-based metrics and CHM-based metrics, and (ii) to construct inferences in the form of confidence intervals for large area structural complexity parameters. The novelty of the study includes assessment of forest structure in Mediterranean forests in the form of multi-species and multi-layered structures resulting from irregular intervals of unplanned and non-standard silvicultural interventions. Although ALS data have been used to predict forest structure in Mediterranean forests (e.g., Morsdorf et al., 2010; Bottalico et al., 2014), the reported studies were conducted in forests managed using standard silvilcultural approaches but not in forests whose complexity results from irregular and non-standard management. A map and an inference for a selected index are provided as a practical example of how the findings of the study can be applied.

2. Material and methods

2.1. Study areas

The study was carried out in two Italian study areas, one in Tuscany and one in Sardinia (Fig. 1). The Tuscany study area extends for more than 700 ha of which 540 ha (77%) is forest. The dominant species are conifers (*Cupressus sempervirens* L., *Pinus nigra* Arn.) that originated from reforestation projects carried out between 1909 and 1985 (Gatteschi and Meli, 1994), and oaks (*Quercus cerris* L., *Quercus ilex* L., *Quercus pubescens* L.). Agricultural land uses, especially olive groves, prevail in non-forest areas.

The Sardinia study area extends for more than 17,000 ha of which 6140 ha (36%) is forest. Forests in the study area are dominated by oaks (*Quercus ilex* L.) and conifer plantations (*Cedrus atlantica* Man., *Cupressuss* sp., *Pinus canariensis* Smith, *Pinus halepensis* Mill., *Pinus nigra* Arn., *Pinus pinaster* Aiton, *Pinus pinea* L., *Pinus radiata* Don.). Reforestation projects started in 1923, but the ages of most of the conifer plantations are less than 50 years. Pastures, shrublands and abandoned lands prevail in the non-forest areas.

In both study areas, no scheduled management activities have been carried out for decades, except for recent moderate thinning from below to prevent wildfires in the coniferous forests and irregular "coppice-like" cuts for firewood in the oak forests. Especially in Sardinia, such limited management combined with the effects of wildfires and uncontrolled grazing produces multi-species and multi-layered, irregular structures with shrub understories typical of the Mediterranean maquis and overstories of conifers and oaks that tend to merge and produce continuous closed canopies.

2.2. Field data

Local forest inventories were carried out using tessellation stratified sampling schemes (Barabesi and Franceschi, 2011) based on a 0.4 × 0.4 km grid in Tuscany and a 2.0 × 1.0 km grid in Sardinia (Fig. 1). Although the sampling intensities for the two study areas differ, the relative ratios of grid spacing to total forest area are approximately equal. For each study area, a sampling point was randomly located in forest in each grid unit, producing 41 points in Tuscany and 85 points in Sardinia (Fig. 1). A 13-m radius circular plot was established with centre at each sampling point, and plot coordinates were recorded using a GNSS receiver Trimble Juno 3 B Handheld with 2–5 m positional accuracy. Diameters at breast height (DBH, 1.30 m) were measured for all living trees with DBH ≥ 2.5 cm. In Tuscany, total tree height (H) was measured with a Vertex III device for all trees, but in Sardinia, total tree height was measured only for a sub-sample of trees. For the remaining non-sampled trees in Sardinia, H was predicted using allometric models with DBH as the independent variable. Field work was carried out in 2012–2013 in Sardinia and in 2013–2014 in Tuscany.

2.3. ALS data

In Tuscany, an ALS survey was carried out in winter 2008 with an ALS ALTM (Airborne Laser Terrain Mapper) Gemini sensor that operated at a flight height of 3000 m a.s.l. The sensor recorded two echoes per pulse with an average density of approximately 0.7 points/m^2. In Sardinia, the ALS dataset was acquired in summer