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Combination of optical and LiDAR satellite imagery with forest inventory data to improve wall-to-wall assessment of growing stock in Italy

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ABSTRACT

The acquisition of information about growing stock is a fundamental step in the framework of forest management planning and scenario modeling, besides being essential for assessing the amount of carbon stored within forest ecosystems. Gallaun et al. (2010) produced a pan-European map of forest growing stock by the combination of ground and remotely sensed data. The first objective of the current paper is to assess the accuracy of this map versus the ground data collected during the latest Italian National Forest Inventory (INFC). Next, a new wall-to-wall estimation of growing stock is obtained by combining ground measurements of four regional forest inventories with the CORINE land cover map of Italy and the global canopy height map derived from Geoscience Laser Altimeter System (GLAS) and Moderate Resolution Imaging Spectroradiometer (MODIS) data. More particularly, the growing stock measurements of the four inventories are stratified by ecosystem type and extended over all Italian forest areas through the application of locally weighted regressions to the GLAS/MODIS canopy height map. When compared to the INFC measurements, the new map shows higher accuracy than that by Gallaun et al., particularly for high growing stock values. The coefficient of determination between estimated and INFC growing stocks is improved by about 0.5, whilst the mean square error is reduced from 90 to 48 m^3 ha^{-1}.

1. Introduction

Maps of forest biomass are important data sources for many scientific and practical tasks such as, for instance, carbon sink evaluation, land suitability assessment and landscape biodiversity estimation (Waring and Running, 2007). Particularly, regional scale spatially distributed estimates of forest biomass are useful as input of environmental modeling exercises (Lindner and Karjalainen, 2007). For example, Maselli et al. (2010) showed the utility of such estimates for the prediction of net forest carbon fluxes in Italy.

Traditional inventories based on ground sampling can provide an accurate statistical assessment of forest attributes (Corona, 2010; Corona et al., 2010). However, given the usual sampling intensity, their completion is generally expensive and time consuming. Moreover, the data collected by these sample-based inventories require additional and often complex processing to derive wall-to-wall maps of forest attributes (Maselli and Chiesi, 2006).

Satellite remote sensing techniques are a valuable source of information about forest attributes related to biomass (tree density, basal area, growing stock, etc.) at various spatial and temporal scales. Several studies have been conducted on the integration of ground and optical remote sensing data to map these forest attributes both over Europe (Tomppo and Halme, 2004; McRoberts and Tomppo, 2007) and North America (Franklin, 2001; Franco-Lopez et al., 2001). In particular, Chirici et al. (2008) intercompared the use of parametric and nonparametric growing stock estimation methods in the Mediterranean area.

Based on these and similar studies, an effort has been recently conducted by Gallaun et al. (2010) to map the main forest attributes over the European continent. These authors produced 500 m maps of growing stock and above-ground woody biomass for broadleaves and conifers through the combination of ground and Moderate Resolution Imaging Spectroradiometer (MODIS) data. These maps are a step forward for the characterization of European forests, but are characterized by some shortcomings, which may limit their operational exploitation. First, the accuracy of the maps has not been assessed extensively at per-pixel level, and few point tests made in Central Italy have pointed out notable uncertainty (unpublished data). Second, the growing stock values reported by the

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map are bounded by a maximum of 300 m^3 ha^{-1}, which is commonly exceeded in many sub-Alpine and Alpine areas (IPLA, 2003; Gasparini et al., 2009; Rodeghiero et al., 2010). These problems are partly due to intrinsic properties of the optical remotely sensed data used, whose relationships with growing stock are only indirect, highly variable in space and time and saturated for high green biomass levels (Maselli and Chiesi, 2006; Powell et al., 2010).

Such considerations suggest that improved maps of forest attributes could be obtained by considering alternative, more appropriate sources of remotely sensed data. Among these, the most interesting is provided by LiDAR techniques, which directly assess vertical forest structure by measuring the distance between the sensor and the scattering elements located inside the canopy volume (Lefsky et al., 2002; Thomas et al., 2006; Maas et al., 2008). Numerous investigations have demonstrated that these techniques can be applied to accurately predict several forest attributes, such as mean tree height, basal area and growing stock (Hyyppa et al., 2008; Corona and Fattorini, 2008; Takahashi et al., 2010; Gonçalves-Seco et al., 2011).

As regards regional scale satellite observations, a unique product has been recently provided by the global forest canopy height mapping effort of Lefsky (2010), which integrated LiDAR data from the Geoscience Laser Altimeter System (GLAS) and multispectral MODIS imagery. The global 1-km map produced is informative on mean tree height, which is indirectly related to growing stock (see description in Section 2.2.4). In most European countries additional geocoded information on forest properties are frequently made available at plot level from national or local forest inventories. In Italy the spatial distribution of forest species is available through a national development of the CORINE land cover map of Europe (ISPRA, 2010).

The current paper aims at developing an integrated approach which utilizes all these information sources to produce an improved version of growing stock map over the Italian national territory. In particular, a statistical methodology based on locally weighted regressions is developed and applied to optimally combine plot level ground data from local inventories with the GLAS/MODIS global canopy height and the CORINE land cover maps. The new wall-to-wall estimates of forest growing stock and the original growing stock map of Gallaun et al. (2010) are finally validated against independent regional data collected by the last Italian National Forest Inventory (INFC, see www.infc.it).

2. Study area and data

2.1. Main features of forest ecosystems in Italy

Italy is geographically located between 36° and 47°30′ north latitude and between 5°30′ and 18°30′ east longitude. Its orography is complex due to the presence of two main mountain chains, the Alps in the north and the Appennines in the center-south. Italian climate is also very variable following the latitudinal and altitudinal gradients and the distance from the sea: in general, it ranges from Mediterranean warm to temperate cool. The country is administratively divided into 20 regions (Fig. 1).

According to the CORINE land cover 2006 map (ISPRA, 2010), forest land (including bushland) covers nearly 9.2 million of hectares in Italy. INFC, whose data are based on the FAO forest definition, reports a total extent of forest areas equal to 8.8 million of hectares. 32% of the forest formations are included in the Alpine bio-geographical region, 16% in the Continental region and 52% in the Mediterranean region (sensu Habitat Directive of the European Commission 43/92). According to INFC, the most widespread forest formations are dominated by various oak species (*Quercus* spp.), a fourth of which is characterized by the prevalence of evergreen oaks, and beech (*Fagus sylvatica*). Among conifers, the most abundant forest formations are dominated by Norway spruce (*Picea abies*), followed by pines (*Pinus sylvestris*, *P. nigra*, and the Mediterranean pines *P. halepensis*, *P. pinaster* and *P. pinea*).

2.2. Data used

2.2.1. Regional and national forest inventories

All ground data used in the current investigation, as well as all maps considered, are referred to the same time period (2000–2010), in order to ensure their approximate intercomparability and combinability.

The four regional forest inventories (RFIs) which provided the training data for the current wall-to-wall estimation of growing stock are from Trentino, Piemonte, Molise and Sicilia and cover most of the environmental and management variability of forest ecosystems in Italy (Fig. 1). The main features of these four inventories are summarized in Table 1. The RFI sampling designs of Trentino, Piemonte, Molise and Sicilia were similar. The plot location was selected using an unaligned systematic sampling (USS) (EPA, 2002) design with systematic cells of 0.25 km^2 in Sicily and 1 km^2 in Trentino and Molise. First-phase plots were classified on the basis of land use/land cover by manual interpretation of aerial digital orthophotos. In Trentino the selection of forested first-phase plots to be visited in the field was carried out on the basis of a Probability Proportional to Size (PPS) random sampling method using the timber volume derived from the local management plan as a proxy variable (Rodeghiero et al., 2010; Tonolli and Salvagni, 2007). In Piemonte the plot design was based on a systematic sampling scheme for stratification on a 500 × 500 m UTM grid. In each field plot, all trees with DBH >7.5 cm were measured together with the height and increment of the nearest tree to the plot center and of the dominant tree (IPLA, 2003). In Molise a random subsample of forested first-phase plots were visited in the field to acquire qualitative and quantitative data. In Sicilia a random subsample of forested first-phase plots were visited in the field for assessing qualitative attributes only (e.g. ownership, forest typology, forest health), while a subsample of second-phase plots were visited in the field to acquire quantitative data.

In addition to these regional inventories, growing stock data were taken also by INFC (Gasparini et al., 2009, 2010). This inventory comprised a three-phase sampling (Fattorini et al., 2006): the first two phases were aimed at estimating the forest area and its distribution into different classes according to qualitative attributes (e.g. property, management issues, vegetation structure and conditions, site features, etc.). The third phase was aimed at collecting quantitative measurements of tree and stand attributes by means of ground surveys carried out on about 7000 plots. During this last phase, which was carried out from 2003 to 2006, several forest variables (tree diameters, tree heights, stem diameter increments, etc.) were collected on a plot basis. Statistics from these measurements are provided in an aggregated form for the twenty Italian regions.

2.2.2. Growing stock map of Gallaun et al. (2010)

The Italian part of the Pan-European growing stock map of Gallaun et al. (2010) is shown in Fig. 2. These authors produced 500 m resolution wall-to-wall maps of coniferous and broadleaved growing stock and above-ground carbon stock by combining comprehensive field measurements from 16 national forest inventories with MODIS multispectral imagery. The results were evaluated by comparison with independent regional data and indicated a relatively high growing stock accuracy at this scale (the reported mean absolute error of the estimates is 25 m^3 ha^{-1} for coniferous, 20 m^3 ha^{-1} for broadleaved and 25 m^3 ha^{-1} for total growing stock).

The map of Gallaun shows relatively low forest growing stock values, always bounded by the imposed upper threshold