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

F. Maselli\textsuperscript{a, *}, M. Chiesi\textsuperscript{a}, M. Mura\textsuperscript{b}, M. Marchetti\textsuperscript{b}, P. Corona\textsuperscript{c}, G. Chirici\textsuperscript{b}

\textsuperscript{a} IBIMET-CNR, via Madonna del Piano 10, 50019 Sesto Fiorentino (FI), Italy
\textsuperscript{b} EcoGeoFor – Università del Molise, Contrada Fonte Lappone snc, 86090 Pesche (IS), Italy
\textsuperscript{c} Consiglio per la ricerca e la sperimentazione in agricoltura, Forestry Research Centre (CRA-SEL), Arezzo, Italy

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
map are bounded by a maximum of 300 m³ 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 Chiari, 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° north latitude and between 5° and 18° 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 inter-comparability 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) method with systematic cells of 0.25 km² in Sicily and 1 km² in Trentino and Molise. First-phase plots were classified on the basis of land use/land cover by manual interpretation of 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; Tonelli 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 (JPLA, 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 m³ ha⁻¹ for coniferous, 20 m³ ha⁻¹ for broadleaved and 25 m³ ha⁻¹ for total growing stock).

The map of Gallaun shows relatively low forest growing stock values, always bounded by the imposed upper threshold
Fig. 1. Spatial distribution of the seven FTs listed in Table 2 derived from the CORINE map, with superimposed boundaries of the 20 Italian administrative regions; the names indicate the four regions whose local forest inventories were considered in the present work.

Table 1
Main characteristics of the four regional forest inventories used to train the growing stock estimation in Italy (see text for details).

<table>
<thead>
<tr>
<th>Region</th>
<th>Publication year</th>
<th>Number of field plots available</th>
<th>Sampling design</th>
<th>Plot features</th>
<th>Growing stock definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trentino</td>
<td>2003</td>
<td>150</td>
<td>USS on 1 km grid + PPS</td>
<td>Plots of 600 m². All trees with DBH &gt;2.5 cm surveyed.</td>
<td>Include the whole above-ground tree (stem + branches + slash)</td>
</tr>
<tr>
<td>Piemonte</td>
<td>2003</td>
<td>13,750</td>
<td>Systematic sampling based on a 500 × 500 m UTM grid intersection.</td>
<td>Plots of variable radius (from 8 to 15 m) with the criteria to include at least 12 trees with DBH &gt; 17.5 cm. All trees with DBH &gt; 7.5 cm surveyed.</td>
<td>All live woody parts with DBH &gt; 4.5 cm</td>
</tr>
<tr>
<td>Molise</td>
<td>2010</td>
<td>304</td>
<td>USS on a 1 km² hexagon grid</td>
<td>2-concentric plots of: 4 m radius: DBH &gt; 4.5 cm 13 m radius: DBH &gt; 9.5 cm</td>
<td>All live woody parts with DBH &gt; 4.5 cm</td>
</tr>
<tr>
<td>Sicilia</td>
<td>2009</td>
<td>1303</td>
<td>USS on 500-m grid + three-phase sampling for stratification scheme</td>
<td>2 concentric plots of: 4 m radius: DBH &gt; 4.5 cm 13-m radius: DBH &gt; 9.5 cm</td>
<td>All live woody parts with DBH &gt; 4.5 cm</td>
</tr>
</tbody>
</table>
(300 m$^3$ ha$^{-1}$). All Alpine areas have constant values close to this threshold, from East to West; along the Apennines, the maximum growing stock is lower than this value and the minima are concentrated in the hottest areas of the peninsula.

2.2.3. CORINE land cover map

A forest type map was derived from the CORINE land cover 2006 map of Italy (ISPRA, 2010). The CORINE dataset of Europe classifies forests at 1:100,000 scale (minimum mapping size of 25 ha) in three general classes: broadleaf, coniferous and mixed (3rd legend level) (EEA, 2002). A more detailed version (4th legend level) instead classifies forests and other wooded land in 26 classes on the basis of the dominant species, maintaining the geometric and thematic congruency with the original CORINE dataset (ISPRA, 2010). In a previous work (Maselli et al., 2006), this vector dataset was rasterized at 1 km spatial resolution grouping the original 26 classes into 12 main forest types (FTs). Among these forest types, the seven most widespread and representative over the Italian territory were selected following auto-ecological criteria (see Chiesi et al., 2007, for details). The main features of these seven forest types are summarized in Table 2 and their spatial distribution is shown in Fig. 1.

The 4th legend level of the CORINE land cover map of Italy indicates that the distribution of forest species follows both altitudinal and longitudinal gradients, with typical continental species (beech and fir/spruce) found mainly in the Alps and in the highest Apennine zones. The warmest areas are covered by Mediterranean macchia and Holm oak.

2.2.4. Global forest canopy height map

A global forest canopy height map was obtained by Lefsky (2010) from the combination of Geoscience Laser Altimeter System (GLAS) and MODIS data (Fig. 3). First, image segmentation of 500 m MODIS data was applied to produce a global map of 4.4 million forest patches. Where a GLAS transect intersected a patch, its height was calculated from the GLAS observations directly. Regression analysis was then used to estimate the heights of those patches without GLAS observations. The accuracy assessment indicated moderately strong relationships for predicting the 90th percentile patch height, with a mean root mean square error of 5.9 m and mean coefficient of determination equal to 0.67.

In Italy, the densest forest areas show similar canopy heights (around 30 m) which seem to be only partly related to different biomass levels. Table 2 provides the average canopy height for each forest type. These heights mostly follow auto-ecological considerations: the highest values are observed for beech and fir/spruce, which also correspond to the most productive forests, while the
lowest values are found for macchia and Holm oak forests, which are spread in water-limited areas.

3. Data processing

The current study aimed at producing wall-to-wall estimates of forest growing stock in Italy by combining ancillary, remotely sensed and ground data. In particular, the research evaluated the possibility of using a limited number of ground measurements, which are labor intensive and expensive to collect. Since the numbers of field plots surveyed in the four inventories were very different (Table 1), all ground data of Trentino and Molise were used for the training phase, while the data of Piemonte and Sicilia were reduced by randomly selecting numbers of plots which allowed an approximately uniform sample distribution over the four regions (Table 2).

The extrapolation of the ground data over the GLAS/MODIS canopy height map was complicated by the different spatial representativity of the ground and remotely sensed data used. The ground samples, in fact, were collected over relatively small plots

---

**Table 2**

<table>
<thead>
<tr>
<th>FT</th>
<th>Dominant forest species</th>
<th>CORINE definition</th>
<th>Area (km²)</th>
<th>Average growing stock from INFC (m³ ha⁻¹)</th>
<th>Average canopy height from GLAS/MODIS (m)</th>
<th>Number of field plots considered</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Evergreen oaks</td>
<td>Holm oak</td>
<td>8778</td>
<td>72</td>
<td>10.72</td>
<td>97</td>
</tr>
<tr>
<td>2</td>
<td>Deciduous oaks</td>
<td>Mediterranean broadleaves</td>
<td>34,521</td>
<td>97</td>
<td>12.30</td>
<td>430</td>
</tr>
<tr>
<td>3</td>
<td>Chestnut</td>
<td>Chestnut</td>
<td>9596</td>
<td>176</td>
<td>19.61</td>
<td>130</td>
</tr>
<tr>
<td>4</td>
<td>Beech</td>
<td>Beech</td>
<td>12,119</td>
<td>231</td>
<td>21.44</td>
<td>249</td>
</tr>
<tr>
<td>5</td>
<td>Plain/hilly conifers</td>
<td>Mediterranean pines</td>
<td>4312</td>
<td>131</td>
<td>7.38</td>
<td>144</td>
</tr>
<tr>
<td>6</td>
<td>Mountain conifers</td>
<td>White fir/Norway spruce</td>
<td>15,768</td>
<td>379</td>
<td>21.00</td>
<td>248</td>
</tr>
<tr>
<td>7</td>
<td>Mediterranean macchia</td>
<td>High maquis</td>
<td>3779</td>
<td>–</td>
<td>6.29</td>
<td>78</td>
</tr>
</tbody>
</table>

---

Fig. 3. GLAS/MODIS canopy height map of Italy with superimposed boundaries of the 20 Italian regions.
placed within forest areas (Table 1), while the GLAS/MODIS data represent the average canopy height of all trees included in each 1 km pixel, which is usually reduced if forests are mixed with other cover types. This observation was confirmed by the correlation found between the CORINE forest fraction and the GLAS/MODIS canopy height images (r = 0.753 on a per-pixel basis). Some trials indicated that this phenomenon could affect the relationships between growing stock and GLAS/MODIS canopy height, thus reducing the efficiency of the whole estimation process. This problem was alleviated by applying the method proposed by Maselli (2001), which uses cover class fraction images to estimate different endmembers of an observed variable (i.e., variable values which would correspond to pure classes) for each pixel. As demonstrated in the same work, these endmembers can reproduce within-class variations of the variable and are therefore more suitable than the original values for the description of local vegetation properties. The method was applied to the GLAS/MODIS canopy height image of Italy based on the CORINE 2006 forest fraction image and produced a map descriptive of the canopy height, which would be found if the entire national territory was covered by forests.

The extrapolation of the ground growing stock measurements was carried out by applying locally weighted (or calibrated) regressions to this endmember canopy height map. The general principles of locally weighted regressions were put forward by Cleveland and Devlin (1988), developed by Brunsdon et al. (1996) and introduced into the remote sensing community by Maselli (2002). Mathematically, they consist in computing a regression model for each estimation point by weighting the values of the reference samples to give preferential consideration to the nearest reference pixels. The computation of local statistics allows the consideration of spatially variable, nonstationary relationships between the independent and dependent variables, which can reduce the efficiency of conventional regression methods (Brunsdon et al., 1996; Maselli, 2002). This is relevant to the present application, since the relationships between canopy height and growing stock are affected by several spatially variable factors, such as altitude, latitude, soil fertility, management practices, etc.

According to the evidence from literature about a general linear relationship between growing stock and canopy height (e.g., Corona et al., 2012; Montaghi et al., 2013), a locally weighted regression model of growing stock on GLAS/MODIS canopy height can be written in the form:

\[ \hat{GSV} = A^* + B^* \times CH \]  

where \( \hat{GSV} \) is the estimated growing stock, \( A^* \) and \( B^* \) are the locally weighted intercept and slope regression coefficients, and \( CH \) is the canopy height, respectively. The coefficients, \( A^* \) and \( B^* \), are derived for each image pixel from relevant statistics computed by giving different weights to the \( N \) reference pixels. These weights can be computed by a negative exponential function of the spatial Euclidean distance, which is regulated by the distance range (Maselli, 2002).

The relationships between growing stock and canopy height are expected to vary with forest type. This was confirmed by a preliminary analysis of the relevant averages reported in Table 2. To address this variability locally weighted regressions were developed and applied separately for each FT. First, locally weighted regression models were trained using the growing stock measurements of each FT derived from the regional inventories. This training phase considered always all data points and large distance ranges (500–1000 km) in order to make the developed regression models applicable over the entire national territory (i.e. also over regions not covered by the ground samplings). Next, these models were applied to all 1 km pixels fully or partly covered by the FT as derived from the CORINE map. Finally, the estimation of total growing stock \( (GSV_{tot}) \) was carried out by weighting the seven growing stock maps obtained for relevant CORINE land cover fractions:

\[ GSV_{tot} = \sum_{i=1}^{7} FC_i \times GSV_i \]  

where \( FC_i \) and \( GSV_i \) are the CORINE fractional cover and growing stock of FT \( i \) for the pixel examined.

### 3.1. Accuracy assessment

The accuracy assessment of the growing stock values was carried out using the aggregated INFC data of the twenty Italian administrative regions. First, this assessment concerned the FT growing stock averages of the four RFIs. Regarding the wall-to-wall growing stock estimates, the original 500 m resolution Gallaun’s map was degraded to 1 km by pixel aggregation and superimposed over the other information layers. Next, regional average growing stock values of the considered FIs were extracted from this and the new map considering only 1 km pixels almost fully covered by a single FT \( (FC > 0.9) \). The extracted averages were compared to the INFC values considering only the Regions where the presence of each forest type was significant (at least 10 pure 1 km² pixels). The analysis did not consider macchia (FT7), for which INFC measurements were not available. The accuracy assessment was carried out first separately for each forest type and then considering all forest types together. The global accuracy assessment was repeated twice, the first time excluding growing stock values from the four training regions and the second excluding values not reported by Gallaun’s map (i.e., higher than 300 m³ ha⁻¹). In all cases the accuracy obtained was summarized using the coefficient of correlation \( (r) \), the root mean square error \( (\text{RMSE}) \) and the mean bias error \( (\text{MBE}) \).

### 4. Results

The regional growing stock estimates reported by the four RFIs here considered are close to those from INFC (Fig. 4). Growing stock
discrepancies between INFC and RFIs are more evident for mountain forest, which are spread in ecologically diversified zones of Alps and Apennines.

The pure forest canopy height map obtained by the spatially variable endmember identification method is shown in Fig. 5. With respect to the original GLAS/MODIS map (Fig. 3), the influence of forest fraction variability is almost completely removed. Consequently, canopy height varies much more smoothly following the main altitudinal and latitudinal gradients in Italy, i.e. increasing with elevation and from South to North.

The final total growing stock map obtained by Eq. (2) (Fig. 6) shows a high spatial variability and seems to capture all previously mentioned altitudinal and longitudinal gradients; the most productive forests are distributed in the North-East of Italy and at relatively high altitudes.

Table 3 reports the results of the accuracy assessment of the Gallaun’s and new growing stock maps carried out for each FT. The correlations between INFC and Gallaun’s growing stocks are very variable, ranging from −0.32 to 0.78; large errors are found particularly for mountain FTs (beech and mountain conifers) due to notable underestimation. The growing stock estimates of the new map are mostly more accurate: the accuracy is strongly enhanced for four FTs, virtually unmodified for FT5 and reduced for FT3. The within-class agreement between measured and estimated growing stocks, however, remains moderate. This is mainly due to relatively low correlations which exist between RFI growing stocks and canopy heights.

The global accuracy statistics of the wall-to-wall estimates are reported in Figs. 7 and 8 for the Gallaun’s and the new map, respectively. In the former case, the accuracy is moderate ($r = 0.571$, RMSE = 90 m$^3$ ha$^{-1}$, MBE = −13 m$^3$ ha$^{-1}$); the greatest errors are found for high growing stocks which are strongly underestimated. This tendency is corrected by the new map, where only a slight positive global bias is observed. The use of the RFI data markedly improves the accuracy both in terms of correlation coefficient ($r = 0.904$) and errors (RMSE = 48 m$^3$ ha$^{-1}$, MBE = 11 m$^3$ ha$^{-1}$) (Table 3).

Table 4 provides the accuracy found for the two maps either by excluding data from the four selected RFIs and by considering only growing stock values lower than 300 m$^3$ ha$^{-1}$. Also in these cases the best results are obtained by the new map both in terms of correlation coefficient and RMSE; the slight tendency to overestimation of this map is also confirmed.
Fig. 6. Growing stock map produced by the procedure here proposed in m³ ha⁻¹.

Table 3
Results of the comparison carried out for each FT between the regional growing stock averages reported by INFC and those obtained from the growing stock map of Gallaun et al. (2010) and from the new map.

<table>
<thead>
<tr>
<th>FT</th>
<th>N samples</th>
<th>Gallaun map</th>
<th>New growing stock map</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>r</td>
<td>RMSE (m³ ha⁻¹)</td>
</tr>
<tr>
<td>1</td>
<td>9</td>
<td>0.087</td>
<td>48</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>0.259</td>
<td>79</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>0.778</td>
<td>34</td>
</tr>
<tr>
<td>4</td>
<td>17</td>
<td>-0.320</td>
<td>86</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>0.716</td>
<td>50</td>
</tr>
<tr>
<td>6</td>
<td>8</td>
<td>-0.198</td>
<td>186</td>
</tr>
</tbody>
</table>

* Significant correlation, P < 0.05.
** Highly significant correlation, P < 0.01.

Table 4
Results of the comparison between the regional growing stock averages reported by INFC and those obtained from the growing stock map of Gallaun et al. (2010) and from the new map; the accuracy is computed first excluding the data from the four RFI regions and next considering only growing stock values reported by the map of Gallaun et al. (2010) (i.e. lower than 300 m³ ha⁻¹).

<table>
<thead>
<tr>
<th>Excluding RFI regions</th>
<th>Excluding INFC growing stock &gt;300 m³ ha⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>N samples</td>
<td>Gallaun's map</td>
</tr>
<tr>
<td></td>
<td>r</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------------</td>
</tr>
<tr>
<td>54</td>
<td>0.569</td>
</tr>
<tr>
<td>59</td>
<td>0.540</td>
</tr>
</tbody>
</table>
inventories were regressed on global canopy height gridded values obtained from the integration of GLAS and MODIS data. The influence of varying forest fractions on the canopy height map was first reduced by the application of a spatially variable endmember identification procedure. Locally weighted regression models were then developed and applied separately for each main forest type, using the CORINE cover fraction images to reconstruct a final growing stock map for the entire national territory.

The quality of this map is affected by the basic characteristics of the information layers utilized. A first problem is due to the use of RFI data which are partly inconsistent with those of INFC. Actually, small growing stock discrepancies were found between INFC and RFI that can be attributed to numerous factors, among which the use of different FT definitions and/or sampling methods in the various inventories and the collection of small ground samples for the least extensive FTs/regions.

The information brought by the global GLAS/MODIS canopy height map is only partly related to growing stock. Mean canopy height, in fact, is generally combined with basal area through species- and age-specific factors for the computation of growing stock (La Marca, 1999). The current lack of basal area and age information is therefore expected to affect the accuracy of the growing stock estimates. This problem is exacerbated by the intrinsic uncertainty which affects the global GLAS/MODIS canopy height estimates (see Lefsky, 2010 for details). Another factor to take into consideration is related to the different spatial support of the canopy height map (1 km$^2$) with respect to the RFI ground measurements (generally fractions of hectare, see Table 1). The effects of both these factors are intrinsically intermingled with those coming from the previously mentioned different representativity of ground and GLAS/MODIS data and are alleviated by the method applied to extract spatially variable canopy height forest endmembers. That method, in fact, enhances the comparability between ground and GLAS/MODIS data by limiting the possible influence of other land cover types and reducing the noise contained in the canopy height estimates. On the other hand, the reduction in spatial detail which is brought by the method is only marginally influential since growing stock variability is mostly due to FTs (see point below).

The negative impact of all mentioned drawbacks is further attenuated by the use of locally weighted regression procedures. These procedures, in fact, are capable of providing nearly unbiased mean estimates over sufficiently large areas (i.e. within the distance range) also in presence of noisy and non-stationary relationships between the independent and dependent variables (Brunsdon et al., 1996; Maselli, 2002). This implies notable advantages for the estimation of growing stock on regional to national scales in heterogeneous and irregular terrains.

The CORINE land cover map is also affected by thematic and geometric errors, whose magnitude is discussed in ISPRA (2010). The use of this map, however, is fundamental in the current case, due to the large growing stock differences which characterize the considered FTs (Table 2). This implies that the stratification into seven FTs brings a significant information gain on the spatial variability of growing stock, which is clearly visible in the final map.

When compared to the INFC data, the new growing stock map is significantly more accurate than the corresponding pan-European map by Gallaun et al. (2010). When considering growing stock aggregated at regional scale the RMSE currently found for the latter map (around 53 m$^3$ ha$^{-1}$) is higher than that declared by the authors for the entire European territory (32 m$^3$ ha$^{-1}$). This discrepancy can be partly attributed to the presence in Italy of many mountain forests, whose high growing stock values are strongly underestimated. Both this tendency and the general low accordance between Gallaun’s and INFC regional growing stock values

5. Discussion and conclusions

The integration of inventory and mapping data is emerging as a major issue for the development of programs that monitor and assess land and multiple environmental functions (Corona et al., 2011). From this perspective, the present paper was aimed at providing a forest growing stock map of Italy based on the combination of a limited number of local forest inventory plot data with digital maps derived from remote sensing imagery. Distinctively, samples of growing stock measurements from four regional forest

![Figure 7](image1.png)

**Fig. 7.** Comparison between the regional values of growing stock provided by INFC and those derived from the map of Gallaun et al. (N=67; **highly significant correlation, P<0.01**).

![Figure 8](image2.png)

**Fig. 8.** Comparison between the regional values of growing stock provided by INFC and those currently produced (N=67; **highly significant correlation, P<0.01**).
are mostly corrected by the new map, which, at the same spatial scale, shows a significantly lower RMSE (around 39 m² ha⁻¹).

These results indicate that the proposed procedure is capable of producing reliable wall-to-wall estimates of forest growing stock also in topographically and environmentally complex areas such as those of the Mediterranean bioregion. Similar methodological approaches of data integration could be applied in other countries, while the new Italian growing stock map can be used to guide further environmental modeling exercises.

Acknowledgements

The Italian Ministry of Education, University and Research funded this study under the FIRB2008 program, project “Modeling the carbon sink in Italian forest ecosystems using ancillary data, remote sensing data and productivity models” C_FORSAT (code: RBFR08LM04, national coordinator: G. Chirici).

We would like to thank Damiano Giannelle at Foundation Edmund Mach for the inventory data of Trentino, Roberto Cibella of Regione Sicilia for those of Sicilia, Fabio Giannetti of I.P.L.A. S.P.A. for those of Piemonte.

Thanks are finally due to an anonymous JAG reviewer whose comments improved the quality of the original manuscript.

References


Corona, P., 2010. Integration of forest mapping and inventory to support forest management. Forest 3, 59–64.


