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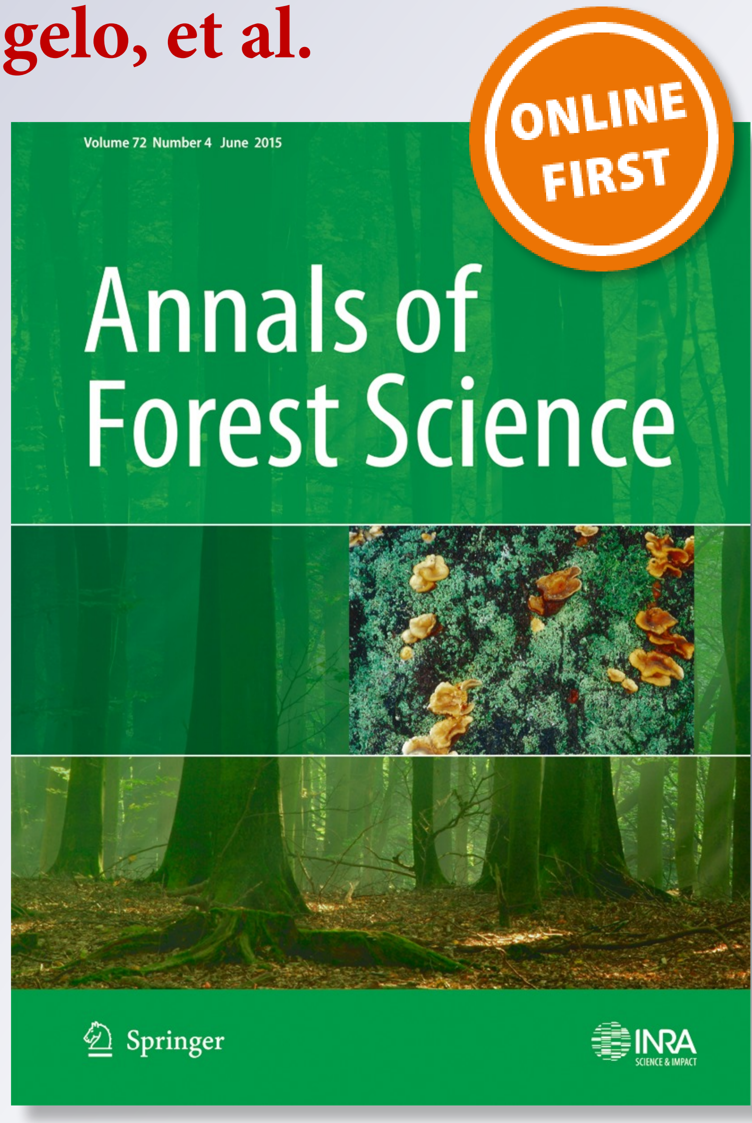

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ORIGINAL PAPER

Estimating belowground biomass and root/shoot ratio of *Phillyrea latifolia* L. in the Mediterranean forest landscapes

Pasquale A. Marziliano [1] · Raffaele Lafortezza [2] · Umberto Medicamento [2] · Leonardo Lorusso [3] · Vicenzo Giannico [2] · Giuseppe Colangelo [2] · Giovanni Sanesi [2]

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Abstract

• ***Key message*** **This study developed and tested models to predict the belowground biomass and root/shoot ratio using aboveground field measures. The predictive power of such indirect measurement is useful for a rapid and reliable assessment of the biomass of the Mediterranean species.**

• ***Context*** Forest biomass estimation has been simplified by the availability of indirect methodologies for automatic measuring. However, most of the information on forest root systems is largely unexplored due to the difficulty in estimating belowground biomass (BGB) at large scale. A plausible approach to investigating forest BGB is to establish a relationship between a number of dendrometric parameters related to the aboveground vegetation (AGB) (e.g., tree diameter and height) and the belowground component of the total biomass.

• ***Aims*** This work presents findings for indirect measurements of BGB in the typical Mediterranean landscapes focusing on sclerophyllous vegetation, specifically *Phillyrea latifolia* L. The purpose of the present study is twofold: (a) to develop a model explaining the BGB distribution of *P. latifolia* based on field data for dendrometric parameters, and (b) to understand how the ratio between BGB and AGB varies according to stem diameter as a proxy of plant growth.

• ***Methods*** A total of 50 *P. latifolia* plants were randomly selected in the study areas and considered for excavation. Individual plants were analyzed to determine AGB and BGB development. A number of models were developed and tested to predict the BGB and root/shoot ratio using aboveground field measures. Allometric equations were employed to predict the AGB and BGB and relative partitioning in the *Phillyrea* community.

• ***Results*** Models for *P. latifolia* AGB and BGB estimation that include crown diameter and stem height measures augment the models' predictive power. When used alone, the predictive power of the root collar diameter appears to be overestimated, while its effect is stronger for a subset of observations with larger crown diameter and stem height. The root/shoot ratio values of plant species typically related to the Mediterranean context seem to be largely superior to the ratio values of trees and forests.

• ***Conclusions*** The model is ideally suited to incorporate indirectly measured tree height for a rapid and reliable assessment of the biomass of single Mediterranean species. Further research might include replication of the same studies in different geographic areas of the Mediterranean and in-depth analyses of AGB.

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Contribution of the co-authors All the authors contributed equally to the manuscript.

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Keywords Sclerophyllous vegetation · Biomass distribution · Root/shoot relationships · *Phillyrea latifolia* L. · Mediterranean landscapes

1 Introduction

The belowground biomass of forest landscapes plays a key role in supplying ecosystem services such as those related to

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primary production, carbon storage, soil conservation, and nutrient cycling (Giardina and Ryan 2002; Grünzweig et al. 2007; Litton and Giardina 2008; Liao et al. 2010). However, most of the ecosystem services associated with forest root systems are largely unexplored due to the difficulty in estimating belowground biomass at large scale (Le Goff and Ottorini 2001; Peri et al. 2006; Niiyama et al. 2010; Yuen et al. 2013). Traditionally, destructive methods such as whole or partial root system excavation have been used to investigate belowground biomass in forest ecosystems. These methods allow measuring and describing the root system in terms of root diameter, distribution, and growth. More recently, nondestructive techniques including (mini)rhizotrons and ground-penetrating radar have been proposed to assess plant rooting distribution and growth (Sanesi et al. 2013).

Estimating belowground biomass is therefore a complex process which requires much effort in terms of time and cost for collecting data (Niiyama et al. 2010; Ruiz-Peinado et al. 2013; Marziliano et al. 2014). Although the research conducted on this topic is extensive, quantitative knowledge on belowground biomass distribution in forest ecosystems still remains scarce (Cairns et al. 1997; Brunner and Godbold 2007; Litton et al. 2007). A plausible approach to investigating forest belowground biomass at large scale is to establish a relationship between a number of dendrometric parameters related to the aboveground vegetation (e.g., tree diameter and height) and the belowground component of the total biomass (Drexhage and Colin 2001; Peichl and Arain 2007; Laganière et al. 2010). Dendrometric parameters can be derived from varied sources of information ranging from field measurements to remotely sensed data and generally involve the use of allometric equations (Latifi et al. 2012; Zolkos et al. 2013; Kankare et al. 2013; Ahmed et al. 2013). Furthermore, few investigations have explored belowground biomass in the Mediterranean forest ecosystems with a specific focus on sclerophyllous vegetation (i.e., maquis and garrigue), despite the wide geographic distribution of this component (Ruiz-Peinado et al. 2013).

This study aims to investigate the belowground biomass distribution in sclerophyllous vegetation with a specific focus on *Phillyrea latifolia* L. communities, which are widely distributed in the Mediterranean region. According to the EEA, sclerophyllous shrubs, including the *Phyllirea* genus, cover ~8.7 million ha in the northern part of the Mediterranean area, stretching from Portugal to Turkey (http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-3).

The purpose of the present study is twofold: (a) to develop a model explaining the belowground biomass distribution of *P. latifolia* L. based on field data (i.e., dendrometric parameters) and (b) to understand how the ratio between belowground biomass and aboveground biomass (root/shoot ratio) varies according to stem diameter as a proxy of plant growth. The root/shoot ratio becomes relevant when applied, for instance, to the protective function of woody vegetation, to the extent that slope stability also depends on the proportion of biomass allocated in the belowground portion compared to that aboveground. In this regard, an estimate model for aboveground biomass has also been developed.

2 Materials and methods

2.1 Study sites

Two areas in the southeastern region of Italy were chosen to conduct the investigation, one in the municipality of Putignano (40° 49′ N, 17° 02′ E) (province of Bari) and the second a few kilometers away in the municipality of Ostuni (40° 49′ N, 17° 02′ E) (province of Brindisi). The geological substrate of the study sites consists of Mesozoic carbonate-type rock belonging to the carbonate sequence of the Murge plateau. According to the World Reference Base for soil resources (IUSS WRB 2006) legend, it is classified in the Haplic Luvisols (chromic) soil group. The rock is composed of whitish and fairly compact layers of deposit and lies several hundred meters beneath the surface. The soil is of the clayey type, consisting of "red earth" eluvial and varying in thickness; 50- to 60-cm-thick areas are interspersed with extensive tracts of surface soil and rock outcrops. The surface layer is essentially composed of clay (approximately 35 %) with a fair amount of limestone skeleton (varying from 5 to 30 %) and abundant drainage. The region's annual rainfall (1980–2010) is limited to 634.4 mm over a 72-day period. The seasonal distribution is typical of the Mediterranean climate, with a concentration of rainfall of almost 200 mm in both autumn and winter. Accordingly, rarefactions in spring and summer induce 153.2 and 89.5 mm of rain, respectively. The dry period lasts from June to early September. The meteorological data correspond to the monthly averages from 1951 to 1996 recorded at the weather station of the former National Mareographic and Hydrological Service (SIMN 1951–1996 – Hydrological Annals).

2.2 Data collection

2.2.1 Aboveground biomass

A total of 50 *P. latifolia* L. plants were randomly selected in the study areas and considered for excavation. As a preliminary step, small sample areas were selected to verify the distribution of the plants according to diameter class. The choice of sample plants was coherent with this distribution. Individual plants were analyzed to determine above- and belowground biomass increases. The aboveground biomass (AGB) was separated into stem biomass (SB) and foliage biomass (FB). All branches were included in SB regardless of their size. Before proceeding with root extraction, the following biometric and dendrometric data were measured for each plant: (i) root collar diameter (RCD) (cm). (ii) stem height (*H*) (cm). and (iii) crown diameter (CD) (cm). The latter was calculated according to the crown's orthogonal projection on the ground. Each sample plant was then cut at ground level and the crown (i.e., branches and foliage) removed from the stem. Stem and crown fresh weights were measured using a field dynamometer and recorded. Subsequently, nine sample branches were collected—3 samples each at 50, 100, and 150 cm from ground level. In addition, 5-cm-thick stem samples were obtained at 50 cm intervals from ground level. In the final field phase, all plant samples were labeled and bagged for laboratory investigation.

2.2.2 Belowground biomass

P. latifolia is a drought-adapted tall shrub which is typically found in well-preserved habitats at mid-elevation. The rooting pattern of *P. latifolia* is characterized by one primary root extending vertically with many short, finer branches, some of which develop into prominent horizontal secondaries with lateral branches (Sack et al. 2003). Where soil depth does not exceed 50–60 cm, the root apparatus of older plants can be deeply affected by the soil characteristics (texture, skeleton), also in terms of architecture and distribution (Schiller et al. 2002). Sample plant roots were harvested at a depth of 50 cm by mechanical extraction coupled with manual excavation to collect total belowground biomass (BGB). Further vertical penetration of the root systems was inhibited by the geological substrate (mentioned in 2.1 Study sites). The lateral extent of the excavation was carried out in relation to the presence of the roots of the plant considered. It was not possible to predetermine a variance of this amplitude of the selected sample. This approach allowed the recovery of the root biomass but resulted in being lengthy and costly precision work, as previous authors have highlighted. All root systems were extracted from the soil, regardless of root diameter (i.e., fine, medium, and wide). The roots were separated from the soil particles and sediments by gentle shaking and water spraying; the fresh weight was measured in field with a dynamometer and recorded. Finally, 5-cm-thick root samples were cut at distances of 0, 20, and 40 cm from the stump. For laboratory analysis, all root samples were labeled, bagged, and stored.

2.2.3 Laboratory analyses

All stem, branch, and root samples were analyzed in the laboratory to calculate dry weights. A standard method (UNI 9091/2) was employed to determine the moisture content of the samples. The samples were dried in a forced-air stove at 103 °C for 72 h until a constant weight was reached; weighing accuracy was 0.2 %.

2.3 Modeling the BGB and root/shoot ratio

The BGB was estimated using different models based on dendrometric variables or a combination thereof. Such a procedure represents the standard for an investigation of this type (Ketterings et al. 2001; Zianis et al. 2005; Anfodillo et al. 2006). Because the literature concerning allometric equations (Zianis et al. 2005) suggests a log-linear transformation of both independent and dependent variables, we used the following equation:

$$\mathrm{BGB} = \alpha + \beta_1\mathrm{RCD} + \beta_2\mathrm{CD} + \beta_3 H + \beta_4\mathrm{RCD}^2 + \beta_5\mathrm{CD}^2 + \beta_6 H^2 + \beta_n\,\text{interaction terms}_n \quad (1)$$

and its logarithmic (linear) form:

$$\ln\mathrm{BGB} = \alpha + \beta_1\ln\mathrm{RCD} + \beta_2\ln\mathrm{CD} + \beta_3\ln H + \ln\beta_n\,\text{interaction terms}_n \quad (2)$$

The same procedure was replicated to estimate the AGB for a further investigation of the root/shoot ratio. Models were run over the whole set of available independent variables using a

Table 1 Descriptive statistics of the attributes measured on the sampled trees; the Shapiro-Wilk test shows that all attributes have a normal distribution

Variable	Mean	Min	Max	SE	SD	Skewness	Kurtosis	SWT Stat	SWT Sig
RCD (cm)	3.8	1.7	7.0	0.20	1.40	0.54	−0.49	0.955	0.055
H (cm)	190.1	98.0	323.2	7.40	52.34	0.25	−0.25	0.978	0.473
CD (cm)	112.5	28.6	236.5	7.08	50.04	0.48	−0.34	0.960	0.091
FB (kg)	0.94	0.03	2.81	0.11	0.78	0.94	−0.09	0.967	0.179
SB (kg)	5.16	0.14	16.20	0.61	4.34	0.91	0.17	0.960	0.092
AGB (kg)	6.10	0.17	19.01	0.72	5.11	0.92	0.13	0.966	0.160
BGB (kg)	4.17	0.22	14.25	0.50	3.57	0.88	0.23	0.955	0.054
TB (kg)	10.27	0.39	33.26	1.20	8.50	0.90	0.14	0.969	0.217

RCD root collar diameter, *H* stem height, *CD* crown diameter, *FB* foliage biomass, *SB* stem biomass, *AGB* aboveground biomass, *BGB* belowground biomass, *TB* total biomass, *SE* standard error, *SD* standard deviation, *SWT* Shapiro-Wilk test (n=50)

Table 2 Proportions among plant biomasses

	As a percent of AGB	As a percent of TB
Foliage biomass	15.41	9.15
Stem biomass	84.59	50.24
Aboveground biomass	100	59.40
Belowground biomass	*68.36*	40.60

The value in italic indicates the root/shoot ratio (n=50)

AGB aboveground biomass, *TB* total biomass

specific procedure to select the best supported model. To this end, we fitted several linear models based on the Akaike Information Criterion (AIC) and then used a stepwise selection model simplification procedure applying the *stepwise regression* and using R v.3.0.3 (R Development Core Ream 2008). This process allowed us to simplify the models and obtain better statistics. The model with the lowest AIC value at each stage was selected. The best supported models for both BGB and AGB were compared against a null model represented by the simplest model (i.e., allometric model) with RCD as an independent variable. Because the best model is a compromise between simplicity and fitness, the adjusted root squared (adj r^2) was calculated to finally choose the model with the best balance between the amount of explained variance and the AIC. Lastly, the estimated values of the BGB and AGB allowed obtaining the root/shoot ratio, both in absolute terms and in relation to plant diameter.

3 Results

3.1 Descriptive statistics

The main descriptive statistics of the measured variables, all with normal distribution, are summarized in Table 1. The average RCD of the *P. latifolia* species sampled was 3.8 cm, while the mean *H* was 190 cm and the CD slightly more than 100 cm. The BGB and AGB were approximately 4.2 and 6.1 kg, respectively; the average total biomass (TB) was 10.3 kg. The standard deviation of all variables was high due to the broad range of sample plants investigated. The root/shoot ratio was about 0.68. Photosynthetically active FB represented approximately 15 % of the AGB and 9 % of the TB, while the BGB represented about 41 % of the TB. Other proportions among plant biomasses are shown in Table 2.

3.2 Best supported models

The model variables were scattered against each other to gain a general understanding of their behavior. Figure 1 clearly shows (using Pearson's index) how RCD is strongly

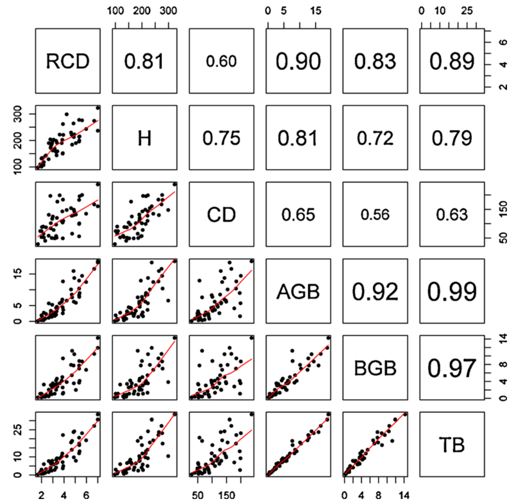

Fig. 1 Scatterplot matrix with Pearson correlations. *AGB* aboveground biomass, *TB* total biomass; n=50

correlated with both TB and its epigeous component (AGB), but also that RCD prevails over *H* and CD in predicting BGB. However, the BGB results could be biased due to the greater difficulty in quantifying the total root system. Finally, RCD is strongly correlated with *H*, but the relationship between RCD and CD is weaker than that between H and CD. The shape of TB-*H* suggests a shift in this relationship after a specific *H* level. Subsequently, the estimated biomass related to the RCD ratio was plotted in relation to the changing biomass type. As expected, the slope was steeper for TB, being the sum of BGB and AGB (Fig. 2). Interestingly, the ratio was steeper for the estimated AGB than for the BGB.

When predicting BGB, the combined RCD and CD variables and their interaction term led to a higher adj r^2 than when using RCD alone (72 % explained variance as opposed to 69 %, see Table 3) and a lower AIC (−51.94). Nonetheless,

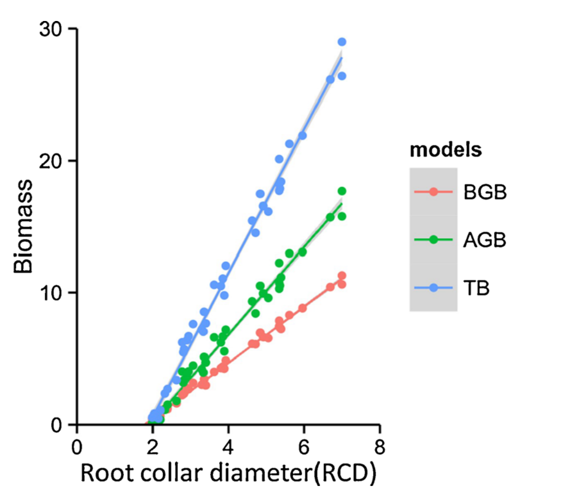

Fig. 2 Relationship between biomass (BGB, AGB, TB) and root collar diameter (*RCD*). Field data are shown as *points* and estimated values as *solid lines*; n=50

Table 3 Akaike Information Criterion (AIC) stepwise model selecting procedure

Models	ln BGB			ln AGB		
	adj r^2	AIC	Delta AIC	adj r^2	AIC	Delta AIC
Null model		9			11.46	
ln RCD+ln CD+ln D*ln CD	0.72	−51.94	42.9	0.85	−82.56	72.3
ln RCD+ln CD	0.71	−51.32	42.3	0.83	−76.65	66.4
ln RCD+ln CD+ln H	*0.71*	*−49.90*	*41.0*	*0.83*	*−76.30*	*66.0*
ln RCD+ln *H*	0.70	−49.29	40.3	0.81	−71.38	61.1
ln RCD	0.69	−48.42	39.4	0.79	−48.75	38.5
ln *H*	0.59	−34.55	25.5	0.70	−36.29	26.0
ln CD	0.37	−15.25	6.2	0.50	−22.63	12.3

The best supported model is in italic type (n=50)

BGB belowground biomass, *AGB* aboveground biomass, *adj* r^2 adjusted root squared, *RCD* root collar diameter, *CD* crown diameter, *H* stem height

comparing the model including the RCD*CD interaction term where *H* replaces RCD*CD, performances did not substantially change in terms of adj r^2 (Table 3). The model fit better when considering AGB as a dependent variable with the explained variance reaching 85 %. Model selection was carried out by testing all possible combinations between independent variables and their interactions. The model illustrated in Table 3 is a subset of all the models that were analyzed and tested. At the end of the modeling process, we found that the model based on ln RCD+ln CD+ln *H* was able to explain a significant amount of the BGB variance 0.71 and AGB variance 0.83 while reducing the AIC value by at least two units.

For BGB and AGB, the best supported model $\ln y = \ln\alpha + \beta_1 \ln\mathrm{RCD} + \beta_2 \ln\mathrm{DC} + \beta_3 \ln H$ was then estimated on a subset of 40 of 50 randomly selected observations. The remaining ten observations were used as actual data to evaluate the model's fit (Fig. 3).

The best supported models were compared to the baseline allometric equation $\ln y = \ln\alpha + \beta_1 \ln\mathrm{RCD}$ to evaluate the gain in predictive and explanatory power. The estimated coefficients (Table 4) suggest that an increase in RCD determines a greater positive effect on the AGB compared to the BGB. Moreover, both the CD variable first and then the *H* variable appear to have a defined role in refining the model.

3.3 Model validation

A leave-one-out cross-validation (LOOCV) procedure was used to test the robustness and predictive value of each regression model. This procedure involves several iterative steps; for each step, one observation is kept out from the calibration of the model and the resulting equation is used to predict the value of the excluded observation. The root-mean-square error of cross-validation (RMSEcv) can be calculated at the end of the procedure and compared to the standard error of the (linear) regression (RMSE). A close agreement between RMSE and RMSEcv indicates that the model is robust and has good predictive value (Michaelsen 1987; Andersen et al. 2005).

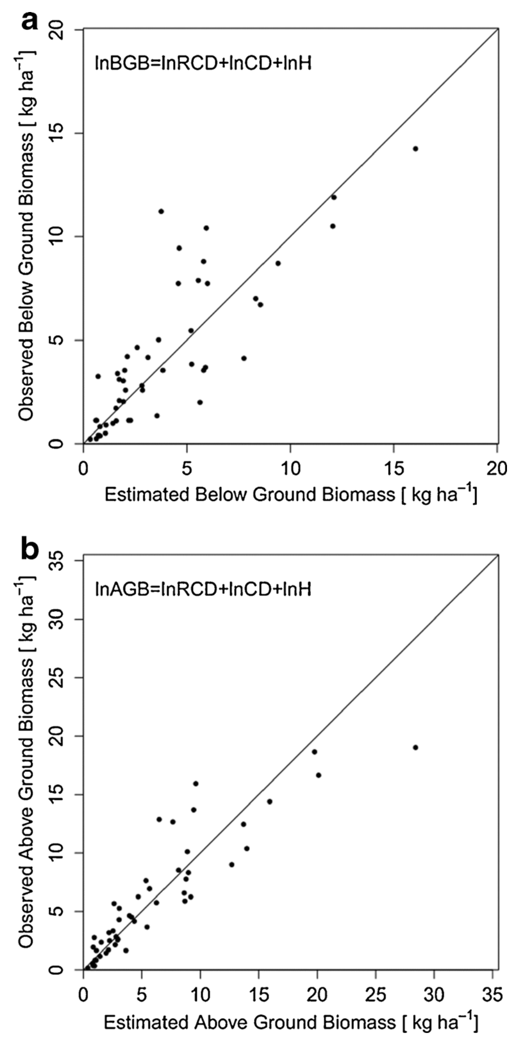

Fig. 3 Observed and estimated values for below- and aboveground biomass; n=40

Table 4 Regression parameters for the selected models

Variable	$\ln y = \ln\alpha + \beta_1 \ln \mathrm{RCD}$		$\ln y = \ln\alpha + \beta_1 \ln \mathrm{RCD} + \beta_2 \ln CD + \beta_3 \ln H$	
	ln BGB	ln AGB	ln BGB	ln AGB
ln RCD	2.40	2.56	2.05	2.12
ln CD			0.31	0.44
ln *H*			0.15	0.14
α (constant)	−2.08	−1.88	−3.86	−4.05
adj r^2	0.71	0.83	0.73	0.86

Estimations were conducted over a data set subsample. Regressions were run over a subset of 40 randomly selected observations ($n=40$)

BGB belowground biomass, *AGB* aboveground biomass, *RCD* root collar diameter, *CD* crown diameter, *H* stem height

Results of the LOOCV procedure are illustrated in Table 5. For each model predicting BGB, AGB, and TB, cross-validation revealed that the differences between RMSE and RMSEcv are not significant. The predicted vs. observed diagram in Fig. 3 (panels a and b) allows to visually understand the aforementioned measures of errors. The same model was run on subsamples of increasing CD (Fig. 4) and *H* classes (Fig. 5). Overall, the model performed quite well for all the CD and *H* classes, but the effect of RCD was stronger for the larger classes.

3.4 The root/shoot ratio

Figure 6 illustrates the trend of the root/shoot ratio with an increase in RCD. The curve was plotted using the estimated root/shoot ratio values in the model $\ln y = \ln\alpha + \beta_1 \ln\mathrm{RCD}$, where y stands alternatively for BGB and AGB. On average, the root/shoot ratio was about 0.68. However, this value changed significantly according to RCD; in particular, the root/shoot ratio decreased as plant size increased (Fig. 6). For plants with RCD ranging from 1 to 1.5 cm, the root/shoot ratio was approximately 0.80 whereas for larger plants, this value decreased. For plants with a RCD of 7 cm, the ratio was approximately 0.58.

4 Discussion

Very few studies have investigated the topic of biomass and carbon content in plant species that make up the "Mediterranean maquis." Nevertheless, these forest communities are of major importance in the biophysics of the Mediterranean ecosystems for both their relevance in the dynamics and function of ecosystems as well as their extensive land cover (Navarro Cerrillo and Blanco Oyonarte 2006). Indeed, many studies employ aboveground tree biomass to determine the size, strength, and dynamics of shrub/small tree populations (Armand et al. 1993; la Marca et al. 1998).

The results of the present study have led to estimate the AGB and BGB for *P. latifolia* L., one of the most common shrub species of the Mediterranean maquis ecosystems. As a rule, such studies allow to perform an estimation of the biomass of different plant components: stem, branches, and foliage. Statistical indicator values for all the equations developed in our study were consistently significant and demonstrated a strong adaptability to the values observed.

P. latifolia L. appears to be characterized by an elevated stem biomass and a reduced number of small leaves, a FB that represents about 15 % of the AGB. This value is inferior to that recorded by Armand et al. (1993) for *Phillyrea* plants in the Mediterranean region of France, where FB averaged 27 % compared to the AGB. Much lower values were reported by Topić et al. (2009) for the island of Brac in Croatia, where FB represented 7 % of the AGB. Moreover, the variation in the percentage of FB decreased (from 16 to 14 %) with an increase of plant diameter; this trend was also observed in the Mediterranean region of France and highlighted by Armand et al. (1993).

As for the root/shoot ratio, a literature analysis suggests that in the Mediterranean environment, the average value is

Table 5 Difference fit measures for the baseline and best supported model

Model	RMSE [kg]	RMSEcv [kg]	RMSE_norm [%]	RMSEcv_norm [%]
ln BGB=ln RCD+ln DC+ln *H*	2.06	2.21	0.15	0.16
ln AGB=ln RCD+ln DC+ ln *H*	2.54	2.79	0.13	0.15

RMSE root-mean-square error, *RMSEcv* root-mean-square error for cross-validation, *RMSE_norm* normalized root-mean-square error, *RMSEcv_norm* normalized root-mean-square error for cross-validation, *BGB* belowground biomass, *AGB* aboveground biomass

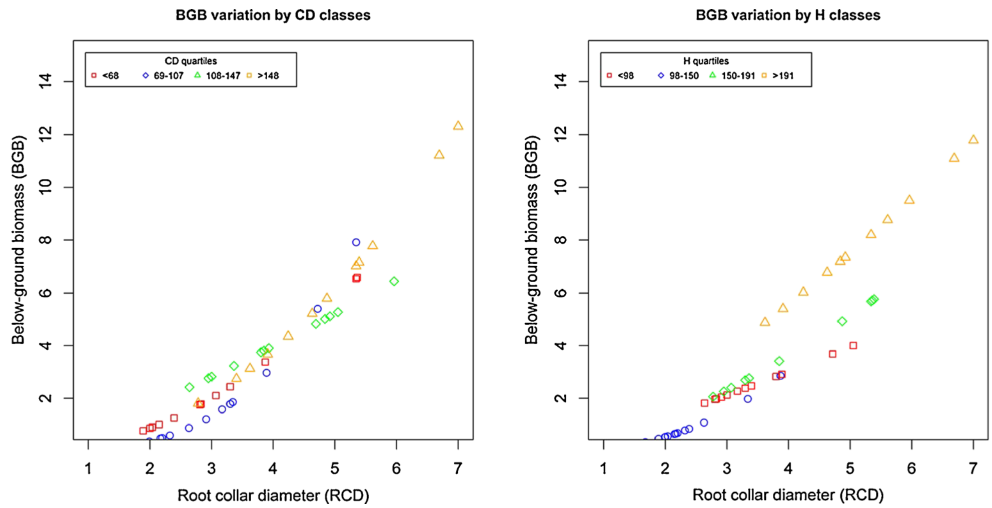

Fig. 4 Belowground biomass (*BGB*) on root collar diameter for crown diameter (*CD*) and height (*H*) classes

generally above 0.4, with values oftentimes higher than the unit (e.g., Caravaca et al. 2003). A study conducted in sclerophyllous Mediterranean forests (of *Quercus ilex*) in the Montseny Mountains of the northeastern Spain (Canadell and Roda 1991) reported that the mean root/shoot ratio was 0.41, whereas the root/shoot ratios of single-stemmed trees were not linearly correlated with diameter. Silva and Rego (2004) in Central Portugal studied the root/shoot ratio in 40 Mediterranean shrubs from 18 species. The root/shoot ratio ranged from 3.7 in *Arbutus unedo* to 0.1 in *Cytisus multiflorus*, with a mean ratio of 0.84. In a study conducted in the southeastern Spain, in reference to the Mediterranean shrubs, Almagro et al. (2010) also estimated a mean root/shoot ratio of 0.84. Ruiz-Peinado et al. (2012) reported root/shoot ratios equal to 0.32 for *Q. ilex*, 0.30 for *Olea europaea*, and 0.81 for *Ceratonia siliqua*. Some studies highlight the fact that the root/shoot ratio values of plant species typically related to the Mediterranean context seem to be largely superior to the ratio values of trees and forests. For the latter, Cairns et al. (1997) described a mean root/shoot ratio ranging from 0.20 to 0.30, with an average value of 0.26 and maximum value of 0.80. As reported by Ulrich et al. (1981), the ratio tends to decrease with tree growth. Accordingly, our data confirmed this last finding (Fig. 6).

The basic allometric equation adopted to estimate biomass yielded good results. Though mainly employed and calibrated for forest stands, where the measured diameter is breast height, the equation demonstrated its explanatory power even in *Phillyrea* communities where the measured diameter is RCD. By using this equation, it is possible to account for most of the variability of tree biomass in forest stands simply by determining the diameter, as previously pointed out by other authors (Anfodillo et al. 2006).

Concerning the best supported model, the literature presents studies that estimate biomass according to the crown's projection on the ground (Lyon 1968), indicating that when height is taken into account, the regression model increases in significance. Our data confirmed this finding and provided

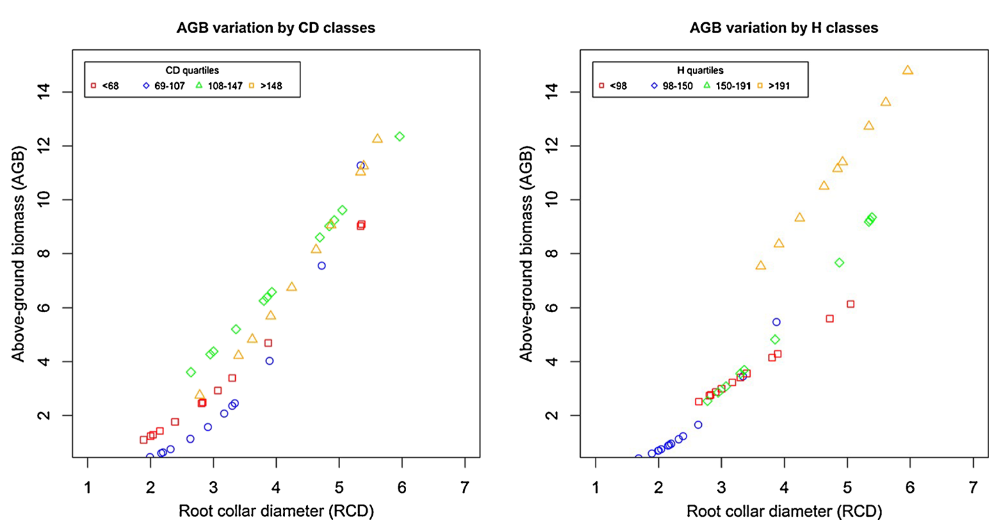

Fig. 5 Aboveground biomass (*AGB*) on root collar diameter for crown diameter (*CD*) and height (*H*) classes

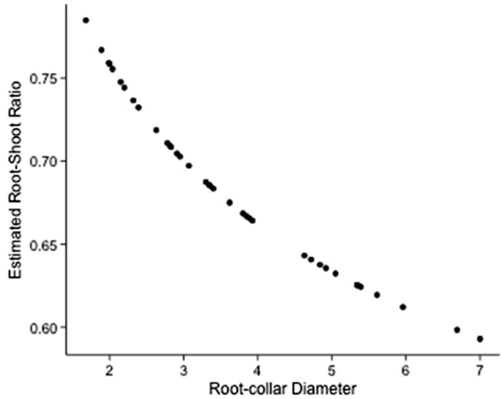

Fig. 6 Relationship between root/shoot ratio and root collar diameter (*RCD*). The curve has been obtained from estimated values of the BGB and AGB

evidence that no relevant improvement is attainable with different model specifications.

The study results prompted us to use this model to incorporate indirect *H* measures (e.g., LiDAR measures) rather than directly quantified measures to obtain faster, easier, and less costly BGB estimates, especially for large forested areas. The models developed herein can thus be employed to obtain a rapid and reliable assessment of the biomass of a single Mediterranean species (stems or foliage) for regulating grazing practices or for calculating thermal energy pursuant to wildfires.

5 Conclusions

The models for the prediction of biomass, though related to a specific case study, are a tool of considerable utility for both ecological and silvicultural purposes. Outcomes, as those of this study, become more meaningful when considering (i) the paucity of studies and lack of tools available to estimate root biomass in the case of sclerophyllous vegetation and maquis and (ii) the negligible distribution of these species in the Mediterranean basin.

A better understanding of the biomass in Mediterranean maquis/garrigue communities can provide useful information not only on their growth but also on the resource dynamics of such ecosystems (i.e., in terms of the ecosystem services they provide). The analyses performed to obtain the biomass data of *Phillyrea* spp. in this study should be applied to other species that typify the Mediterranean maquis/garrigue to obtain broad perspectives of ecosystem productivity. Results suggest that including CD and *H*, measures slightly augment the power of indirect BGB and AGB estimation with good predictive value, as confirmed by the LOOCV procedure, implying that this model may be used, for example, to incorporate indirect *H* measures. Further, the predictive power of RCD is overestimated when used alone, while within the selected models, its role changes for larger classes of CD and *H*.

Relevant future research might include the replication of the same studies in different geographic areas of the Mediterranean. In addition, prospective seasonal trends and dynamics (availability of water resources) that have been observed in other garrigue and maquis species might be investigated. Data from this study should contribute to the knowledge concerning the Mediterranean forest landscape estimation and the increased benefits associated with its belowground biomass, especially soil conservation (counteracting desertification), carbon storage, water purification, and nutrient retention.

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