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RESEARCH PAPER

Single-tree crown shape and crown volume models for *Pinus nigra* J. F. Arnold in central Italy

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Abstract

Key message **The crown volume of *Pinus nigra* trees can be modelled as a function of the total crown length and the crown radius at crown base to support forest management practices.**

Context The crown volume of trees is rarely considered in forest management practices and is often approximated to a simple cone or paraboloid whose volume can be broadly derived from costly measurements.

Aims We developed two equations to predict single-tree crown volumes for *Pinus nigra* plantations in Italy based on the analysis of a database with 3578 trees.

Methods Two key crown parameters (total length of the crown and crown radius at crown base) were here modelled using directly measurable mensurational data using Generalise Additive Mixed-effect Model. Afterwards, two functions were then proposed to predict single-tree crown volumes.

Results The fitted models were statistically significant and explaining 57.6% for crown radius at crown base and 87.1% for crown length of the total variance. The power model for single-tree crown volumes calculation showed a mean absolute error around 4.1 m^3 for the upper portion of the crown and 12.1 m^3 for the lower part for a mean absolute relative error of 12.5% and 32.0% respectively for a global value of 16.4%.

Conclusion Single-tree and stand-level data are fundamental to balance forest management trajectories. The provided functions may be used in external dataset to derive indication on the single-tree or stand-level crown volume to be used as indicators of ground coverage.

Keywords Forest management · Silviculture · Forest ecology · Planted forest · Tree modelling

1 Introduction

The spatial distribution of trees across the stand influences the shape and dimension of the crowns which in turn reflect the vitality and growth rates of trees (Pretzsch 2009). In stocked stands, crown shape is affected by a combination of multiple factors, including local climate, site conditions, ontogenetic stage, stand density and competition processes (Shi and Zhang 2003; Ledermann 2010). Accordingly the aerial space occupied by trees' crowns also impacts on the amount of solar radiation on the ground whose has a key role in enhancing all the biological processes in the soil (Coudun et al. 2006; Barbato et al. 2019) and the regeneration dynamics in forests (Page and Cameron 2006). This is also acknowledged as the main factor which forest management practices can modify (Del Río et al. 2017). Actually, crowns features are also sometimes used to attribute social ranks to trees across a stand, driving tree marking for thinning (Soto-Cervantes et al. 2016; Bravo-oviedo et al. 2020).

The relationships between the space occupied by the canopy and other fundamental features of forest ecosystems have been often investigated in literature and mainly aimed at evaluating the levels of animal and plant biodiversity

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(Torras and Saura 2008; Maccherini et al. 2021), measuring the degree of inter and intra-specific competition (Page and Cameron 2006; Fichtner et al. 2013), predicting the mechanical stability of the trees (Wang et al. 1998; Marchi et al. 2017) and assessing the flame speed in the event of fire (Martín Santafé et al. 2014; Kim et al. 2016). The single-tree crown size and therefore its photosynthetic capacity, is one of the main indicators of the effects of silvicultural treatments on the competition between trees in forest stands (Cabon et al. 2018). In this framework, the use of indicators and statistical models to support forest management practices is currently increasing (Mäkelä and Pekkarinen 2004; Holopainen et al. 2014; Sharma et al. 2017; Marchi et al. 2020).

The shape and distribution of the crowns across a stand define its vertical and horizontal layout, a fundamental attribute to understand the processes of growth and competition in forest ecosystems. Several allometric coefficients have been proposed in the literature where the shape of the crown has been related to the variation in crown radius as the distance from the top increases (Pretzsch 2009). These results refer to some of the main and most economically important European tree species and mainly including conifers as *Picea abies* (L.) H. Karst., *Abies alba* Mill., *Pinus sylvestris* L., *Larix decidua* Mill. and *Pseudotsuga menziesii* (Mirbel) Franco. Overall a general approach evaluating the variation of the radius of crown as the distance from the top increases is accepted (Pretzsch 2009). However, no statistical models are currently available in the literature to predict the shape and amount of foliage occurring above the ground in a forest stand.

In the present work, a modelling framework for crown shape and crown volume in unmanaged black pine (*Pinus nigra* J. F. Arnold spp.) plantations is proposed. The main aim of the paper is to provide a simple model to predict the single-tree crown volume exploiting basic mensurational parameters such as the average crown radius (R) and the total length of the tree's crown (L). In this work, the models were here also cross-checked with some mensurational parameters and structural indices widely used in literature to describe the vertical and horizontal structure of forest stands. A practical use of the model is also reported by providing the different impact of two thinning systems on the amount of crown volume at stand level in black pine plantations in Italy and re-analysing a previous study case in the Apennines (Marchi et al. 2018).

2 Materials and methods

2.1 Study areas and raw data

The dataset used to determine the crown profile model and crown volume consists of 3578 black pine trees measured during the SelPiBio-LIFE project (freely available at https://zenodo.org/record/438681#.YLSv05r7SV4). Stands were in two different zones of Tuscany called Monte Amiata (42°56′8″N, 11°38′13″E, mean elevation 780 m a.s.l.) and Pratomagno (45°27′8″N, 9°11′13″E, mean elevation 960 m a.s.l.). The data were collected in 36 circular fixed area sampling plots (15-m radius), half of which were in each study area.

In addition to the already available mensurational data also reported in Cantiani and Marchi (2017), two additional variables were added here: (i.) the mean crown radius (r_{mean}) using the vertical sighting method (Pretzsch et al. 2015) as the quadratic mean of eight crown radii and (ii.) crown radius at crown base (r_{cb}). The raw data were firstly used to derive stand level attributes for each plot (Table 1) and single-tree volumes were calculated using the most recent Italian national forest inventory equations (Tabacchi et al. 2011).

2.2 Crown profile models

According to the literature, we calculated single-tree total crown volume (i.e. the space occupied by the crown) as the sum of the volume of a paraboloid (upper part) and a truncated cone (lower part) as shown in Fig. 1. The basic equations for the volume calculation of the two parts are as follows:

Table 1 Main mensurational parameters of sampled stands derived from the SelPiBio dataset (https://doi.org/10.1007/s13595-017-0648-8)

Site	Species	Density [Trees.ha^{-1}]	Quadratic mean diameter [cm]	Mean height [m]	Basal area [m^2.ha^{-1}]	Volume [m^3.ha^{-1}]
Amiata (45 years)	Black pine	959	24.3	18.1	43.6	386.4
	Other	91	16.7	12.8	1.2	7.7
	GLOBAL	1050	23.6	17.8	44.8	394.1
Pratomagno (60 years)	Black pine	889	29.5	19.2	59.1	538.4
	Other	188	20.5	15.5	9.5	94.2
	GLOBAL	1077	28.7	18.8	68.6	632.6

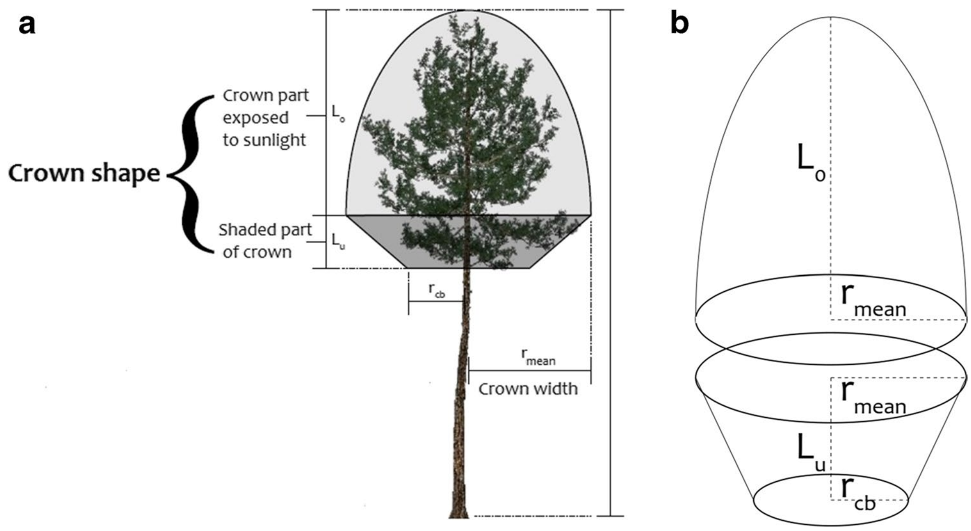

Fig. 1 Graphic representation of crown of a softwood tree according to literature (Pretzsch 2009) and graphical representation of the calculation of crown volume in *Pinus nigra* trees

$$V_{light} = \frac{\pi \cdot r_{mean}{}^2 \cdot L_0}{2} \tag{1}$$

$$V_{shade} = \frac{\pi \cdot \left(r_{mean}{}^2 + r_{cb}{}^2 + r_{mean} \bullet r_{cb}\right) \cdot L_u}{3} \tag{2}$$

where r_{mean} is the average crown radius of the crown, L_0 and L_u are the height of the upper and the lower portion of the crown respectively and r_{cb} is the radius of the smaller circle paced at the bottom of the shaded part of the crown (crown radius at crown base).

This basic structure uses L_0 and r_{cb} as two key parameters to be observed (or calculated somehow) and there is a wide agreement on total length of the crown (L) as predictor for L_0 (and then L_u for difference) as the difference between the total height of the tree and distance of the first living whorl from the ground. According to Pretzsch (2009) which represents the most recent and up to date resource in the field, the most reliable and easy way to derive this parameter is to multiply L times a coefficient ranging between 0.5 and 0.6 according to the target tree species. However, this corresponds (ideally) to the slope of a linear model with intercept forced to zero. Something similar has been used for r_{cb} as a function of the average crown radius. In order to improve this work, a more complex modelling technique has been tested with Generalized Additive Mixed-effects Model (GAMM, Wood and Scheipl 2017) This model has been of the used in literature dealing with forest trees (Pacheco et al. 2018; Poschenrieder et al. 2018; Ferrara et al. 2019; Ravaioli et al. 2019) and is able to handle linear and nonlinear relationships in a mixed effect framework which is very common in forest ecology. The basic structure of GAMM was:

$$Y = s(x) + rnd + \varepsilon \tag{3}$$

where Y is the dependent variable (L_0 or r_{cb}), *s()* denotes a smoothing term to be applied to the predictor and x is the independent variable (L or r_{mean} according to the dependent variable to be modelled). Finally, *rnd* represents the random effect to be used in the model according to the structure of the database and to handle the relationships between the sampled units which may violate the basic assumptions of models (i.e. independence between samples etc.). Finally ε denotes the error term. The GAMM was here used to predict L_0 (and then L_u as $L_u = L—L_0$) and r_{cb} to be used in Eqs. (1) and (2). The structure of GAMMs was:

$$L_0 = s(l) + rnd + \varepsilon \tag{3a}$$

$$r_{cb} = s\left(r_{mean}\right) + rnd + \varepsilon \tag{3b}$$

GAMMs were parametrised using an iterative process to optimise the REML score using the gamm4 R package (Wood and Scheipl 2017) in R environment (R Development Core Team 2020). A cross validation procedure was also performed to compare the fitting according to the Mean Absolute Error (MAE) and Mean Relative Absolute Error (MARE) as well as the amount of explained variance. Once models were fitted the L_0 and r_{cb} values were re-calculated using fitted GAMMs to derive the calculated crown volumes (CCV) and simulating a lack of data in our dataset. Then, the two vectors of crown volume values (i.e. measured and calculated) were tested against each other using the Kolmogorov–Smirnov test.

2.3 Crown volume equations

While all the above-mentioned parameters (L_0, L_u, r_{mean}, r_{cb}) could be directly measured during forest surveys, the use of a more user-friendly approach may fill the gap on the use of crown volume in forest management practices with lower costs and reliable estimates. For this reason, several models were here tested including polynomial functions, exponential functions, linear functions, and power models using the crown volumes (both upper and lower parts) we calculated for all the 3578 trees occurring in our database. Then such models were also compared under ANOVA and post-hoc test to detect statistical differences between the models. The best predictors were selected among the raw basic mensurational parameters such as DBH, total height of the tree, the total crown length and the average crown radius and a stepwise procedure was implemented to select the most meaningful predictors only. A second cross-validation procedure was here performed in order to test the quality of the developed models using MAE and MARE as indicators of goodness of fit. Once models were validated, a correlation analysis was run to assess whether the calculated crown characteristics were somehow connected to some structural diversity and inter-tree competition indexes. Among the crown shape features we calculated the ground coverage excluding overlaps (COV), ground coverage with crown overlaps (RIC), volume of the upper portion of the crown (UCV), volume of the lower portion of the crown (LCV), total volume of the crown (TCV). The stand structure indices were the size differentiation index (SDIFF) (Pommerening 2002), quadrant index (QI) (Cox 1971), Clark and Evans (CE) (Clark and Evans 1954), vertical evenness (VE) (Neumann and Starlinger 2001), Latham index (LT) (Latham et al. 1998), Hegyi competition index (Hegyi, Sharma et al. 2017) as well as additional stand-level indicators e.g. number of trees per hectare (N), total basal area per hectare (G.ha), etc. Additionally also a measure of the under canopy Photosynthetically Active Radiation (PAR) was added to the comparison, measured by means of different kinds of ceptometers (Sunfleck SF 80, AccuPAR model PAR-80 e LP-80 -Decagon Devices Inc., Pullman, WA, USA) and according to most recent literature (Wood et al. 2015).

As a conclusive study, the potential application of this tool has been proposed for a practical use. The data coming from two different thinning systems (from below and crown thinning) on black pine plantations from Marchi et al. (2018) were re-analysed here, enriching the already available data (e.g. average DBH, dominant height, number of trees per hectare, total biomass, etc.) with the crown volumes using the developed models. Afterward, the effects of the two thinning systems on the amount of crown volumes in the aerial layers were observed.

3 Results

3.1 GAMM fitting results and comparison with the single-coefficient approach

The L_0 and r_{cb} values generated using the "raw" method proposed by Pretzsch (2009) which were therefore calculated to compare the GAMMs outputs with the only alternative existing approach (i.e. the calculation of a simple multiplier to be used to derive L_0 and r_{cb} values from the total crown length and the average crown radius) showed an average coefficient for L_0 of 0.58 with a maximum value of 2.62 and a minimum of 0.05 demonstrating a wide range of variability between trees for a standard deviation of 0.16 which corresponds to a coefficient of variation of 27%. A similar pattern was then observed for the multiplier for r_{cb} with an average value of 0.61 and a range between 0.18 and 1.24 for a standard deviation of 0.26 and a coefficient of variation around 42%. Overall, the results showed that a large variability was found and that a more complicated modelling framework was necessary such as the GAMM we used to include nonlinear relationships too. The use of the simple multiplier generated a higher MAE around 35% for both L_0 and r_{cb} calculation. The high flexibility of GAMM easily allowed us to fit statistically significant models with an explained variance of 57.55% for L_0 and 84.13% for r_{cb}. A quite small MARE was observed in the cross-validation procedure of 23% for L_0 and 27% for r_{cb}. Models' parameters and their statistical significance are summarised in Table 2.

As expected, the L_0 parameter was more variable across the dataset and consequently the confidence interval in case of longer crowns (i.e. bigger L values) was much wider. Finally, and concerning the comparison between the observed crown volumes and the simulated ones (i.e. crown volumes where L_0 and r_{cb} were calculated using the fitted GAMMs), the Kolmogorov–Smirnov test assessed the equality of the distributions (p value = 0.946) validating the good fitting power of the models.

Table 2 GAMM fitting results. Both models were fitted using a Gaussian family and an identity link function

	GAMM coefficient	Estimate or edf for the smoothing term	Std. error	Ref. df	P value
L_0 fitting	Intercept	4.08126	0.08203	-	$<2\ e^{-16}$
	s(l)	5.5180	-	5.518	$<2\ e^{-16}$
r_{cb} fitting	Intercept	1.18454	0.05516	-	$<2\ e^{-16}$
	$s(r_{mean})$	2.9710	-	3.717	$<2\ e^{-16}$

3.2 Crown volume equations

The total crown length and the average crown radius were the best predictors for robust and parsimonious models for both the upper and the lower portion of the crown. According to the cross-validation results (Table 3), the power model was the most reliable and accurate method to predict crown volumes with a MAE around 4.1 m^3 for the upper portion of the crown and 12.1 m^3 for the lower part for a MARE of 12.5% and 32.0% respectively and a global MARE of 16.4% (this because the amount of volume allocated in the upper portion of the crown is generally more than double than the lowest part). Overall, also the polynomial function used to perform fairly with sometimes higher explained variances but showed higher and MAE and MARE than the power model. Such differences were also statistically significant when compared under ANOVA and the post-hoc test.

According to the cross-validation results, a power model was fitted on the full dataset to derive the coefficients and summary statistics on the functions to be used to calculate single-tree crown volumes in *Pinus nigra* planted forests. The coefficients are shown in Table 4 and a graphical representation of the calculated crown volumes is shown in Fig. 2 and where only integer height classes between 10 and 20 m were included for reporting purposes.

The comparison between the calculated values of crown volume and the other indices or mensurational parameters derived from the raw data is proposed as correlation matrix in Table 5. According to this analysis, the total crown volume (TCV) was correlated with the basal area, the total standing biomass (i.e. volume per hectare), the average DBH, the average height, and the dominant height (i.e. the Site index). TCV was also connected to the volume of the lower portion of the crown (LCV) and the upper part of the crown (UCV). Then, concerning structural parameters, statistically significant correlations were found between crown volumes (UCV, LCV and TCV) and both the proportion of ground covered by canopy (COV) and ground coverage with crown overlaps (RIC). Concerning PAR, a negative correlation was found with LCV and TCV.

Table 4 Estimated coefficients of the final power functions. The basic structure of the function was $Crownvolume = a \bullet b^{(L \bullet R)}$ where L and R are the crown length (total height of the tree minus the crown insertion) and R is the average crown radius

Crown portion	Expl.Var	Coefficient	Estimate	Std. error	Prob(>|t|)
ABOVE	89.94%	*a*	0.094253	0.003447	$<2e^{-16}$
		b	2.059610	0.008925	$<2e^{-16}$
BELOW	81.86%	*a*	0.213974	0.009536	$<2e^{-16}$
		b	1.809397	0.011339	$<2e^{-16}$

The application of this tool is summarised in Table 6 and Fig. 3 with most of the crown volume that was allocated in co-dominant and dominant trees. Such trees were only removed with the crown thinning, a more intense thinning where also higher social classes are harvested than those marked when applying the thinning from below. The results clearly show how, even if most of the current thinning schemes are aimed at reducing the total number of trees per hectares to be removed, the real influence of silvicultural practices should be evaluated in terms of free growing space available for released individuals (i.e. crop trees). The provided model seems able to support forest managers to estimate this parameter more easily and effectively at low cost i.e. few additional measurements are necessary and can be easily obtained by means of optical relascopes or laser scanning techniques.

4 Discussion

The crown volume equations developed under a statistical environment were proved to be robust and applicable in the field of forest science. The significant correlations between predicted crown volumes and the mensurational parameters tested here demonstrate that this tool can be considered an innovative tool in forest management (Pretzsch 2014; Pommerening et al. 2018). As expected, positive correlations

Table 3 Cross-validation results for the 4 tested crown volume models. The cross-validation procedure was repeated 1000 times preserving 75% of the database for training models and 25% for testing, randomly extracted. The standard deviation within single runs is reported between brackets

Crown portion	Fitted model	Var.explained	MAE	MARE
ABOVE	Exponential	80.0% (±5.4%)	20.32 (±2.02)	138.15% (±31.4%)
	Linear	76.8% (±4.5%)	18.31 (±2.83)	162.45% (±34.5%)
	Polynomial	91.3% (±3.1%)	10.21 (±2.11)	59.08% (±16.3%)
	Power	90.0% (±4.4%)	4.14 (±0.63)	12.51% (±2.5%)
BELOW	Exponential	70.3% (±7.7%)	21.36 (±1.63)	174.52% (±29.2%)
	Linear	76.3% (±3.2%)	15.70 (±1.82)	143.90% (±25.8%)
	Polynomial	85.5% (±4.6%)	13.06 (±2.36)	57.54% (±13.4%)
	Power	82.4% (±4.2%)	12.06 (±0.85)	32.16% (±3.9%)

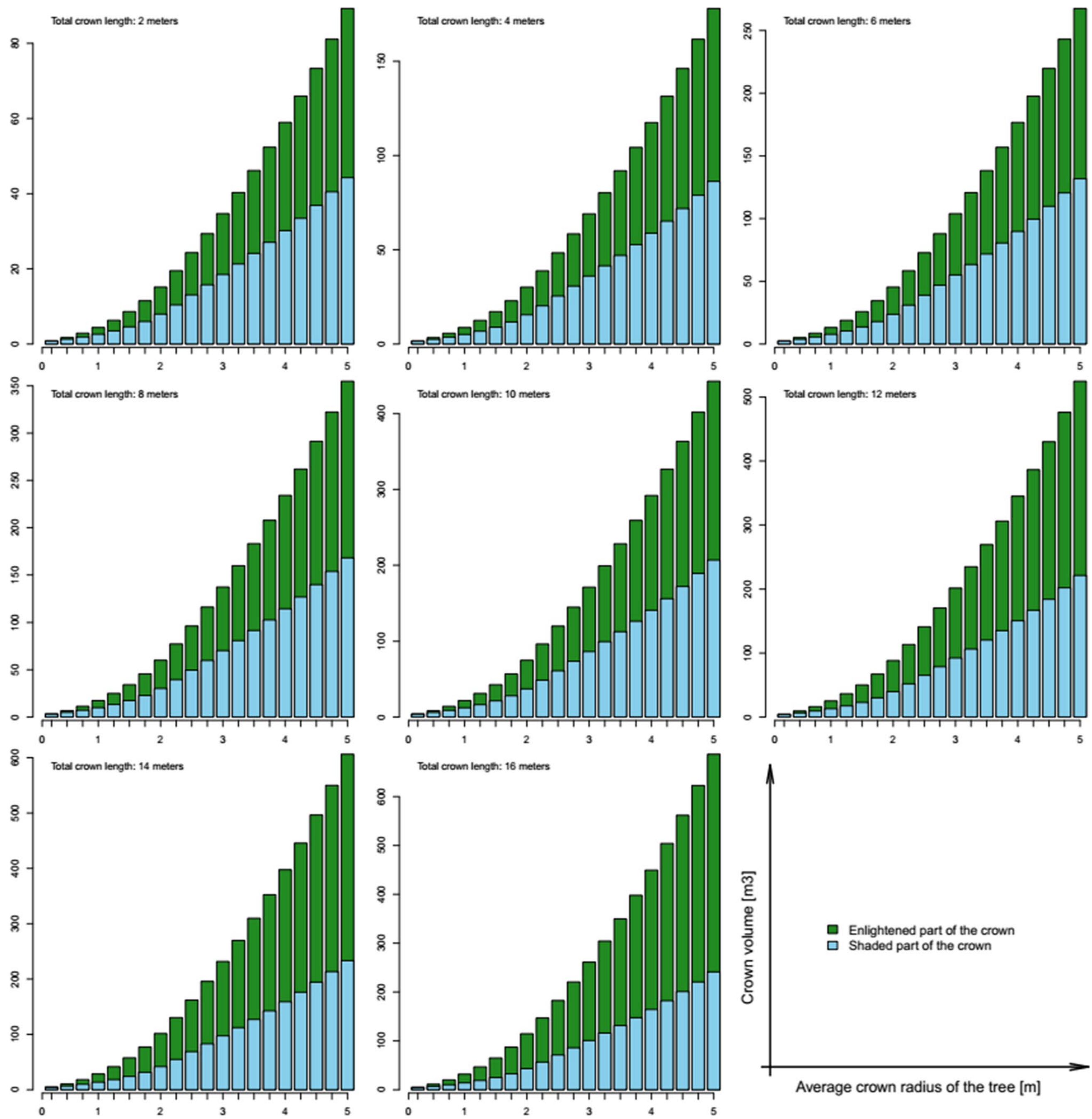

Fig. 2 Estimated single-tree crown volumes for trees between 2 (top-left) and 16 (bottom-right) meters of crown length. The proportion of volume for lower (skyblue) and upper (green) portion of the crown is reported with different colour. The height of the green bar already represents the sum of them. Each bar of each single plot corresponds to a calculation performed with a fixed height but a variable average crown diameter between 0.25 m (first bar, left) and 5 (last bar, right) meters assumed to be the maximum radius a *Pinus nigra* tree can achieve at maturity. Volumes on y-axis are reported in m^3

were found between the canopy volumes and the mensurational parameters closely related to the size of the plants (i.e. basal area, average and dominant height and volume per hectare). Acting on competitive relationships and freeing up space in favour of the best individuals is one of the main objectives of thinning interventions, in particular in forest plantations and youth development stages (Lafond et al. 2014; Del Río et al. 2017). The results of the model suggest that trees with more expanded crown and possibly with the largest expansion located lower should be considered as crop trees to be preserved. This may generate an increase in the photosynthetic capacity of individuals preserved by cutting

Table 5 Nonparametric (Spearman) correlation coefficients (upper diagonal) and p values (lower diagonal) between some structural and competition indices calculated with available raw data and crown volumes (up, down, total). Statistically significant correlation coefficients are shown in bold

	Nr.ha	G.ha	V.ha	aDBH	aH	Hdom	Sdiff	QI	CE	VE	Lt	Hegyi	COV	RIC	PAR	UCV	LCV	TCV
Nr.ha	1	**0.330**	0.223	**-0.367**	**-0.471**	-0.090	0.078	-0.036	0.017	0.104	0.225	**0.640**	0.037	0.068	-0.044	-0.114	0.008	-0.047
G.ha	**0.015**	1	**0.957**	**0.739**	**0.631**	**0.710**	0.022	-0.092	0.051	-0.176	0.044	0.079	**0.333**	0.169	**-0.337**	**0.514**	0.230	**0.401**
V.ha	0.105	**0.000**	1	**0.774**	**0.710**	**0.847**	-0.006	-0.064	0.101	-0.129	0.040	0.030	**0.339**	0.205	**-0.337**	**0.628**	**0.319**	**0.516**
aDBH	**0.006**	**0.000**	**0.000**	1	**0.973**	**0.775**	-0.033	-0.069	0.090	-0.270	-0.138	**-0.377**	**0.367**	0.180	**-0.350**	**0.605**	**0.273**	**0.473**
aH	**0.000**	**0.000**	**0.000**	**0.000**	1	**0.791**	-0.109	-0.065	0.154	-0.235	-0.164	**-0.451**	**0.404**	0.256	**-0.380**	**0.601**	**0.358**	**0.532**
Hdom	0.518	**0.000**	**0.000**	**0.000**	**0.000**	1	-0.124	-0.022	0.200	-0.053	-0.072	-0.247	**0.328**	**0.316**	-0.263	**0.720**	**0.452**	**0.654**
Sdiff	0.573	0.877	0.969	0.814	0.442	0.387	1	0.171	-0.179	-0.142	**0.325**	**0.548**	-0.146	-0.249	0.146	0.080	-0.032	0.015
QI	0.798	0.512	0.648	0.622	0.646	0.879	0.239	1	-0.043	0.125	-0.064	0.157	0.024	-0.127	0.066	-0.065	-0.042	-0.060
CE	0.902	0.717	0.472	0.522	0.276	0.160	0.219	0.772	1	0.022	0.072	**-0.291**	0.263	**0.349**	-0.160	0.105	0.159	0.161
VE	0.455	0.207	0.357	0.051	0.094	0.713	0.329	0.397	0.884	1	-0.051	0.013	-0.194	0.072	0.179	0.140	0.051	0.101
Lt	0.102	0.756	0.776	0.324	0.244	0.614	**0.023**	0.664	0.629	0.735	1	**0.306**	**-0.317**	-0.094	0.275	0.011	-0.011	-0.003
Hegyi	**0.000**	0.573	0.829	**0.005**	**0.001**	0.080	**0.000**	0.287	**0.047**	0.929	**0.040**	1	-0.099	-0.201	0.039	-0.096	-0.059	-0.086
COV	0.792	**0.015**	**0.013**	**0.007**	**0.003**	**0.019**	0.317	0.870	0.074	0.197	**0.034**	0.522	1	**0.666**	**-0.879**	**0.319**	**0.478**	**0.487**
RIC	0.626	0.226	0.141	0.198	0.067	**0.023**	0.084	0.389	**0.016**	0.634	0.540	0.190	**0.000**	1	**-0.544**	**0.322**	**0.728**	**0.666**
PAR	0.749	**0.014**	**0.013**	**0.010**	**0.005**	0.062	0.316	0.657	0.284	0.235	0.067	0.803	**0.000**	**0.000**	1	-0.383	**-0.384**	**-0.484**
UCV	0.410	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	0.583	0.663	0.484	0.354	0.944	0.536	**0.039**	**0.040**	0.080	1	**0.429**	**0.767**
LCV	0.955	0.097	**0.020**	**0.047**	**0.009**	**0.001**	0.828	0.775	0.286	0.735	0.941	0.705	**0.001**	**0.000**	**0.016**	**0.007**	1	**0.909**
TCV	0.734	**0.003**	**0.000**	**0.000**	**0.000**	**0.000**	0.921	0.686	0.279	0.504	0.984	0.579	**0.001**	**0.000**	**0.011**	**0.000**	**0.000**	1

Acronyms: Nr.ha, number of trees per hectare; G.ha, total basal area per hectare; V.ha, standing volume per hectare; aDBH, average DBH; aH, average height of the stand; Hdom, dominant height; Sdiff, size differentiation index; QI, quadrant index; CE, Clark and Evans index; VE, vertical evenness index; Lt, Latham index; Hegyi, Hegyi index; COV, ground coverage without crown overlaps; RIC, ground coverage with crown overlaps; UCV, volume of the upper portion of the crown; LCV, volume of the lower portion of the crown; TCV, Total volume of the crown (LCV + SCV)

Table 6 Summary statistics of the effect of two different thinning methods (low and selective thinning) in two black pine planted forests (Monte Amiata and Pratomagno) where the total crown volume removed was calculated with the models provided in this study

Location	Thinning type	Removed trees	Basal area	Biomass	Crown volume	PAR
AMIATA	Thinning from below	−30.4%	−19.7%	−18.7%	−11.2%	+133%
	Selective thinning	−34.3%	−31.9%	−30.7%	−24.4%	+413%
PRATOMAGNO	Thinning from below	−35.9%	−22.6%	−19.3%	−11.3%	+87%
	Selective thinning	−30.8%	−29.4%	−29.7%	−21.2%	+232%

and an increase in the degree of stability of the stand (Cameron 2002; Ferretti et al. 2014).

The volume of the crown was also directly correlated with some structural indices and negatively correlated with the PAR (i.e. the more crown you have, the less light on the ground can be observed). With respect to the latter correlation, it is interesting to note that the crown component that affects the barrier to light radiation is mainly addressed to the lower portion of the crown: the shadow component. This aspect may be due to the shape of this portion, more like a rectangle or a trapezium than a triangle. In this shape, more leaves and branches are aligned on the same vertical line creating a more solid barrier to sunlight. However, the ratio between the two parts of the crown tends to gradually increase with the total height of the tree (positive correlation) in favour of the upper portion as well as with the increased average crown radius. This is an intrinsic feature of *Pinus* trees due to its light-demanding ecology and a similar behaviour can be expected with other *Pinus* species such as Scots pine but also Douglas fir (Hann 1999).

Parametric and nonparametric models are nowadays seen as mandatory in many research fields, able to provide estimations and confidence intervals at the same time (Aertsen et al. 2010; Petr et al. 2014; Pecchi et al. 2019). The simple multipliers obtained averaging raw data showed to be almost unable to detect the variability of the analysed

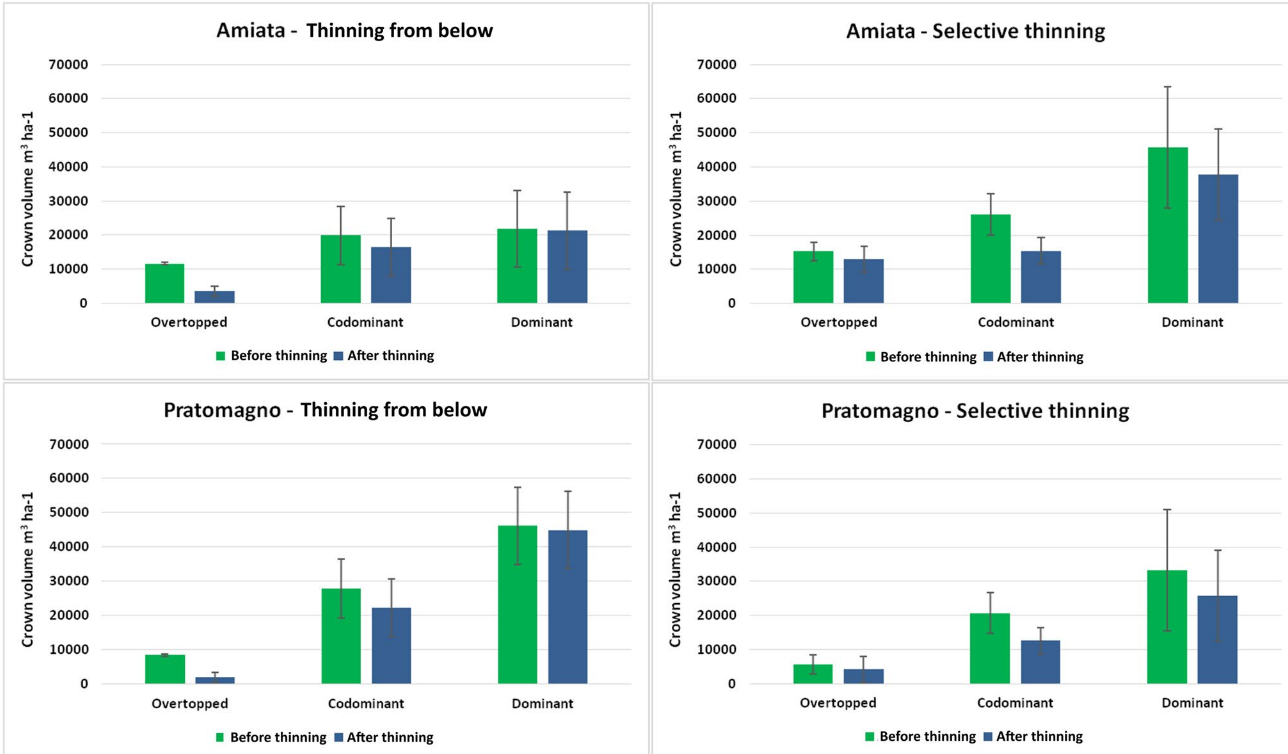

Fig. 3 Crown volume removed across the social classes (ranks) in the SelPiBio study case

phenomena as well as to provide inferences on the output (Bayer et al. 2013; Marchi 2019). The use of GAMM as modelling techniques allowed us to fit L_0 and r_{cb} more properly than using simple coefficients as proposed by Pretzsch (2009). The biological explanation of the model we used, relies on the expected shape of the relationships between the variables. Even if a sigmoid function may also be used to represent the two analysed relationships, the ability of GAMM to fit many different datasets simplified the study, also providing a reliable and statistically sound model. Even if the use of parametric models may be welcome in order to deliver coefficients for standalone calculations, the use of more complex statistical tools is almost compulsory in many research activities to generate reliable estimates and to handle large datasets (Mendoza and Martins 2006; Marchi et al. 2020). The lack of a simple equation to be given to users for mass calculation of crown volumes (e.g. large forest inventory dataset) would have been the main shortcoming of our approach. The coefficients we are proposing for the power function can partially solve the problem being usable also on raw databases if the two basic parameters are available. Such parameters can be easily measured in forest surveys by means of optical relascopes but also derived from laser scanning surveys (Corona and Fattorini 2008; Bayer et al. 2013).

The analysis of the variables that define trees' crown profile and the volume they occupy, provides useful elements to understand the levels of structural diversity of forest ecosystems and therefore, the microclimatic parameters and ultimately the biodiversity levels (Archaux and Bakkaus 2007; Barbato et al. 2019). This is particularity true in black pine planted forests, a dynamic system where biological processes play a fundamental role for future scenarios and ecological successions (Piermattei et al. 2012; Barbato et al. 2019). A very important aspect indeed is the evaluation of the effects of silvicultural treatments on the space occupied by the canopy in forest stands (Chianucci et al. 2016). The here described models might be helpful to quantify the amount of growing space effectively released to the remaining trees without additional and time-consuming field surveys. (Marchi et al. 2018).

5 Conclusions

The crown volume and its qualitative features (e.g. transparency, colour, branches angle etc.) are fair indicators for tree growth and the models here proposed could be considered an additional tool to support the practical management of black pine stands. The use of models to predict crown volumes could be used as tool to evaluate the amount of solar radiation available on the ground (i.e. PAR) and to balance silvicultural treatments to support the transition to more stable and natural forest systems i.e. the climax by mean natural regeneration of native broadleaves with particular ecological requirements.

As follow-up studies, a survey campaign in the same stands with Laser Scanning Tools to obtain measurements of crown volumes to be compared with our predictions may be a fair step forward for our research, also to address the basic assumptions on the crown shape of *Pinus nigra* trees here used.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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