Single tree crown shape and volume models for Pinus nigra planted forests in Italy to support forest management strategies in artificial stands

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Single tree crown shape and volume models for *Pinus nigra* planted forests in Italy to support forest management strategies in artificial stands

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Abstract (350 words)

Background: Tree crown can be considered the engine of trees whose size is a key variable to understand the most important ecological and physiological processes that occur in forest ecosystem. The shape and dimension of single-tree crown are affected by a combination of multiple factors such as lateral competition, fertility as well as forest management practices. Anyway, few models are provided in literature to derive their shape and volume from sampled data except the light transmittance or light measurements under canopy closure (Photosynthetic Active Radiation or Leaf Area Index). The main goal of the study is to present a simple and effective method to predict crown shape and crown volume in artificial black pine plantations in Italy from simple field data. Two key parameters involved in crown volume calculation in literature were here modelled. Such parameters were the distance from the top where the crown expresses its the maximum radius (L_0) and the radius at crown base height (r_{cb}). The analysis of crown profile and volume is based on available knowledge we found in literature (Pretzsch 2009) and where the considered species was not included.

Results: The nonlinear equation results the most adequate for the fitting and able to characterise the ecological processes more properly. Even if just slightly different, the mean absolute error was lower and statistically significant and around 84 cm for L_0 and 36 cm for r_{cb}. Then the use of a modelling procedure also allowed the calculation of confidence intervals and was more powerful than a single multiplier, which is the most common method available in literature. Once compared with field data collected during thinning harvesting, the calculated volumes were correlated with thinning intensities and able to characterise the number of trees removed in each treatment and the increased amount of PAR on the ground.

Conclusions: The proposed model results useful to evaluate the spatial structure of forest stand without sophisticated and time-consuming surveys and could be an additional tool to support the practical management of artificial black pine stands.

Keywords: Forest management; Silviculture; Forest ecology; Planted forest; Tree modelling

Background

The density of trees influences the shape and dimension of the crown which is the real engine of a tree, where all the physiological processes occur such as photosynthesis, respiration and transpiration (Hemery et al. 2005; Pretzsch 2009; Soto-Cervantes et al. 2016). Crown shape is affected by a combination of multiple factors, including local climate, site conditions, ontogenetic stage, stand density and competition processes (Biging and Gill 1997; Shi and Zhang 2003; Ledermann 2010). In addition to growth trends, also the amount of solar radiation on the ground is connected to both trees' density and crown shape characteristics. This driver has a key role in enhancing all the biological processes in the soil (Coudun et al. 2006; Barbato et al. 2019) and the regeneration/successional dynamics in forests (Page and Cameron 2006) and is the main factor modified by forest management practices (Del Río et al. 2017; Cabon et al. 2018). The shape and distribution of the crowns across a stand define the vertical and horizontal layout, a fundamental attribute to understand the processes of growth and competition in forest ecosystems. Several studies have investigated the relationships between the space occupied by the canopy and other fundamental features of forest ecosystems, such as: i) levels of animal and plant biodiversity (Torras and Saura 2008; Barbato et al. 2019) ii) the degree of inter and intra-specific competition (Page and Cameron 2006; Fichtner et al. 2013; Soto-Cervantes et al. 2016); iii) the mechanical stability of the trees (Wang et al. 1998; Marchi et al. 2017); iv) assessment of potential behaviour in the event of fire (Martín Santafé et al. 2014; Kim et al. 2016). However, the distribution, composition and vertical structure of forests are only partly determined by the ecological factors and the needs of the individual species, as these have undergone over time the effects of human activities and forest management (Bengtsson et al. 2000; Fady et al. 2016; Olthoff et al. 2016).

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; Pecchi et al. 2019). The principle behind the indicator concept is that the characteristics of an easily measured feature convey information about more than itself, summarizing and communicating complex information in a way that can be quickly understood (Shi and Zhang 2003; Mc Elhinny et al. 2005). Thus, indicators are of crucial importance to be used for a variety of purposes, such as: describe and diagnose a situation, check the effectiveness of management practices, discriminating among alternative policies, forecast future trends (Lindenmayer et al. 2000; Failing and Gregory 2003; Butchart et al. 2010). Several indicators have been developed to support Sustainable Forest Management (SFM) and part of these are directly derivable from models outputs (Mäkelä et al. 2012).The stand density index (SDI) is probably one of the most used and well known indicator of forest stocking (Pretzsch and Biber 2005; Marchi 2019). This index is represented by a numerical value that captures intensity of competition within forest stands including the volume of the growing stock, age structure and/or diameter distribution, carbon stock and carbon stock changes in forest biomass. Anyway, ecological indicators need to capture the complexities of the ecosystem yet remain simple enough to be easily and routinely monitored (Dale and Beyeler 2001). The (mathematical) simplicity requirements always needs to be achieved with care, without denaturing ecological processes (Marchi 2019).

The single-tree 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). Silvicultural interventions play a fundamental role in the allocation of the foliar mass of forest populations, affecting the competition between trees by modifying the social position (rank) of the released trees, based on the spaces created and the resources ceded by plants that fall when cut. In the present work, two models to predict crown shape and crown volume in artificial *Pinus nigra* Arnold spp. stands are proposed. The main aim of the paper is to present a simple and effective method to evaluate the spatial structure of forest stand without sophisticated and time-consuming surveys from basic mensurational parameters (DBH, height, etc.), widely available in any national forest inventory dataset and including the amount of photosynthetically active radiation (PAR) on the ground under canopy and measured with time-consuming and expensive tools. A practical use of the model is also proposed in the last part of the article by comparing the effects of different silvicultural treatments in black pine artificial plantations.

Materials and Methods

Study areas and raw data

The dataset used to determine the crown profile model and crown volume consists of 4,171 black pine trees measured during the SelPiBio-LIFE project (Cantiani and Marchi 2017). Stands were located 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.) and fully described in Cantiani and Marchi (2017). The data were collected in 36 circular fixed area sampling plots (15-m radius), half of which were in each study area (Fig. 1).

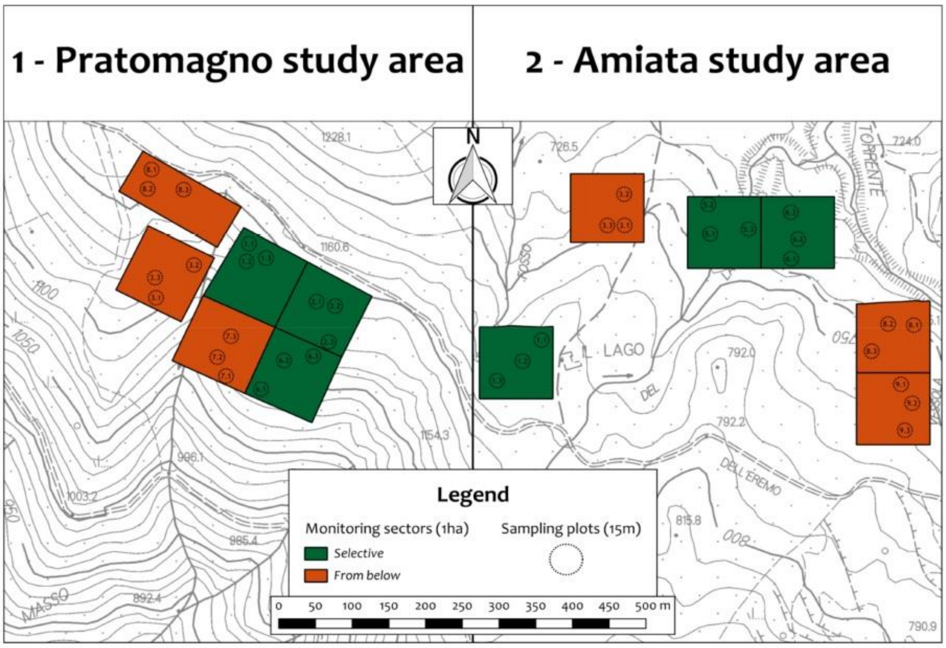

Fig.1 Spatial distribution of monitoring sectors and sampling plots in both of the study areas. The different thinning systems applied are marked with different colours (Marchi et al. 2018).

In each study area, 18 sampling plots randomly located in 6 forest monitoring sectors of 1 ha in size (3 plots in each forest monitoring sector) were identified. For all trees the following variables were measured: a) the diameter at 1.30 m height (DBH) using diameter measurement tape; b) total height (Ht), height of first living whorl (Hc) and height at maximum crown width (Hm) using Vertex III; d) the mean crown radius (r_{mean}) using the vertical sighting method (Pretzsch et al. 2015) as the quadratic mean of eight crown radii, selected to be representative of the crown perimeter and without any prefixed scheme (e.g. N, NE, E, etc..) e) the crown radius at crown base (r_{cb}); f) the total PAR on the ground. Then the total basal area, total standing volume and total crown volume were calculated for each plot (Table 1).

Table 1 Main mensurational parameters of sampled stands derived from the SelPiBio dataset

Site	Species	Density [Trees.ha^{-1}]	Mean DBH [cm]	Mean height [m]	Basal area [m^2.ha^{-1}]	Volume [m^3.ha^{-1}]
Amiata (45 yrs)	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 yrs)	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

Crown profile and crown volume equation

The analysis of crown profile and crown volume structure is currently available for many tree species and based on the use of a model, already used by Central European Authors, evaluating the variation of the radius of crown as the distance from the top increases (Pretzsch 2009). The model uses a segmented approach, dividing the crown (Fig. 2) into an upper (crown part exposed to the sunlight) and lower portion (shaded part of the crown) at the point of the largest crown width.

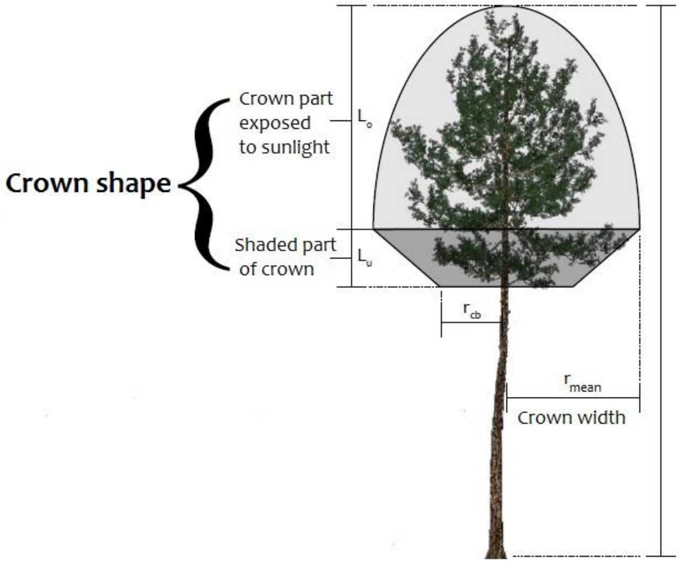

Fig.2 Graphic representation of crown of a softwood tree according to Pretzsch (2009)

Then the total crown volume (i.e. the space occupied by the canopy) is calculated as the sum of a paraboloid (crown part exposed to the sunlight) and a truncated cone (shaded part of the crown). According to this structure (Fig. 3) the equation for the volume calculation of the two parts are as follows:

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

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

where r_{mean} is the average crown radius we obtained from 4 or 8 radial measurements, L_0 and L_u are the height of the crown part exposed to the sunlight the height of the shaded part 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). In this framework, while field data are necessary for r_{mean}, two models can be fitted to estimate/calculate L_0 (and consequently L_u) and r_{cb} properly from commonly available mensurational parameters.

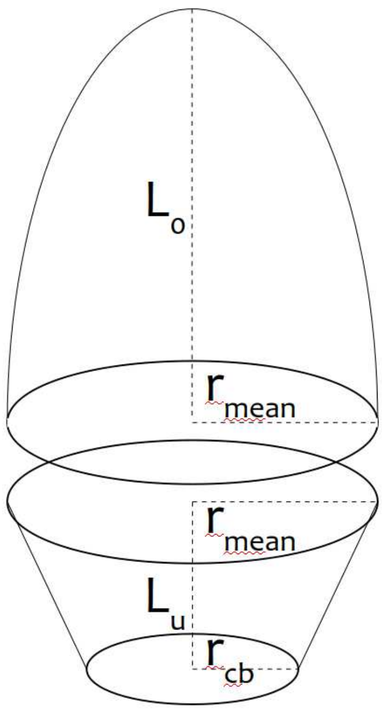

Fig.*2 Graphical representation of the calculation of crown volume in Pinus nigra trees*

Concerning L_0, this is often calculated by means of a simple multiplier ranging between 0.5 and 0.6 according to the target tree species (Pretzsch 2009). which corresponds (ideally) to the slope of a linear model with intercept forced to zero. Anyway, forcing intercept to zero is often risky. While many biological models should be characterised by zero intercept (e.g. the relationship between DBH and height of a tree), this issue never occurs in practice. Therefore, the liner model has been here fitted allowing intercept to be calculated from data:

$$L_0 = \alpha + \beta \cdot L \quad [3]$$

where L is the total length of the crown, derived as the difference between the total height of the tree and distance of the first living whorl from the ground and α and β are the coefficients to be optimised. In addition to model [3] a nonlinear one was fitted too, represented by a power function which often used in ecological studies such as the stand density index calculation (Marchi 2019):

$$L_0 = \gamma \cdot L^{\delta} \quad [4]$$

with L as above and γ and δ as regression parameters. Afterwards the r_{cb} model was parametrised too using the same models (linear and nonlinear) but replacing L_0 and L with r_{cb} and r_{mean} respectively.

All the equations were parametrised using an existing dataset made by more than 4000 *Pinus nigra* trees collected in central Italy across artificial stands. The comparison was made performing a cross validation procedure (CV) using a random subset of around 75% of the data as training and the remaining 25% of records for testing dataset. CV was repeated 10^5 times and the Mean Absolute Error (MAE) and explained variance (i.e. the r squared, R^2) were used as indicator of goodness of fit and used to select the best modelling method, averaged to obtain reliable estimates (means). To assess statistical differences, parametric ANOVA was used on MAE and R^2 values using the fitted model as treatment. Furthermore, 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 light portion of the crown (LCV), volume of the shaded portion of the crown (SCV), 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 derived mensurational parameters such as the number of trees per hectare (N), total basal area per hectare (G.ha), total standing volume per hectare (V.ha), average diameter at breast height (aDBH), average height of the stand (aH) and dominant height (Hdom) we derived from raw data. Finally also a measure of the under canopy Photosynthetically Active Radiation (PAR) was add which was 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 methods already widely tested in the literature (Cutini et al. 2009).

Results

The comparison between linear and nonlinear models showed the power model as the most adequate for fitting with statistically significant coefficients (and regressions) and good predictive power (Fig.

4). Even if slight, the MAE was sensibly lower in both cases and statistically significant under ANOVA (Table 2). The explained variance was of 0.59 for L_0 and 0.75 for r_{cb}. The estimated coefficients are reported on Table 3.

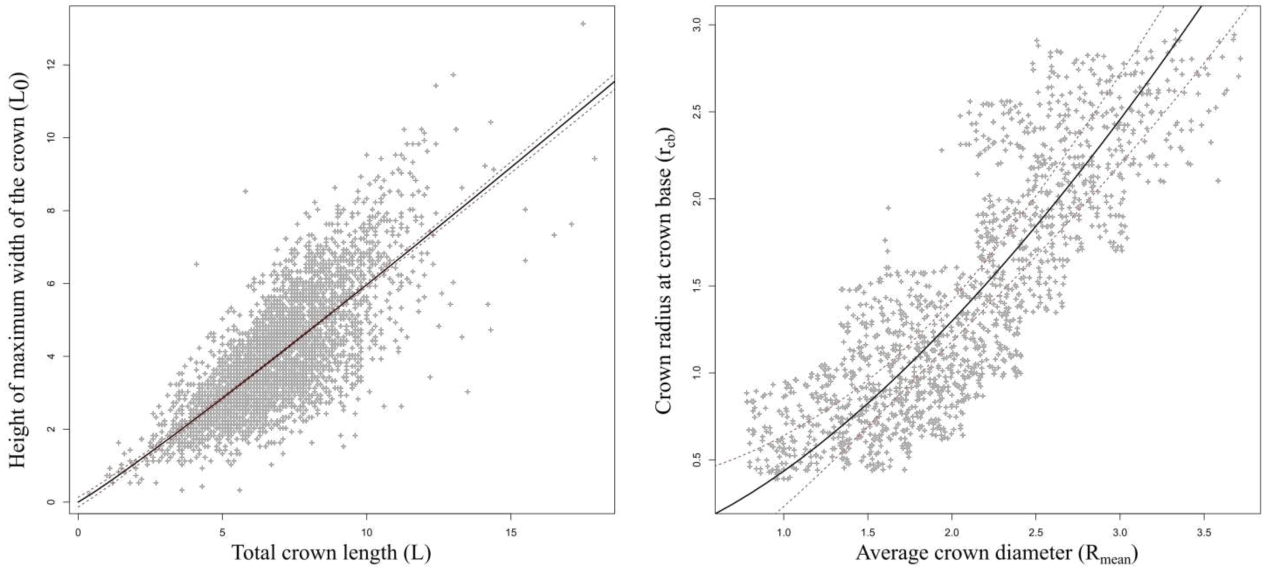

Fig.4 Regression analysis for L_0 (left) and r_{cb} right. Intervals of confidence (upper and lower) are shown as dotted lines

Table 2 Mean Absolute Error (MAE) values obtained from the cross-validation procedure. Number as expressed as meters

Model	**Minimum**	**Median**	**Mean**	**St. deviation**	**Maximum**
L_0 linear	0.76	0.83	0.84	0.02	0.94
L_0 nonlinear	0.76	0.84	0.84	0.02	0.94
r_{cb} linear	0.16	0.36	0.36	0.06	0.63
r_{cb} nonlinear	0.12	0.35	0.36	0.06	0.69

Table 3 Estimated coefficients for equations [4] and [6] for the calculation of L_0 and r_{cb} parameters

Parameter	**Coefficient**	**Estimate**	**Std. Error**	**t value**	**Pr(>|t|)**
L_0	γ	0.5148	0.0178	28.900	< 2e-16 ***
	δ	1.0641	0.0167	63.880	< 2e-16 ***
r_{cb}	γ	0.4363	0.0591	7.389	1.19e-10 ***
	δ	1.5728	0.1535	10.244	4.85e-15 ***

Crown volumes were calculated for each tree and aggregated to obtain plot-level sums. A correlation analysis was then run to assess whether the calculated values were connected to other indices or mensurational parameters derived from the raw data (Table 3).

Table 3 Nonparametric (Spearman) correlation coefficients (upper diagonal) and p.values (lower diagonal) between some structural indices calculated with available raw data and crown volumes (light, shade, total)

	Nr.ha	G.ha	V.ha	aDBH	aH	Hdom	Sdiff	QI	CE	VE	Lt	Hegyi	COV	RIC	PAR	**LCV**	**SCV**	**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**
LCV	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
SCV	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; LCV = volume of the light portion of the crown; SCV = volume of the shaded portion of the crown; TCV = Total volume of the crown (LCV+SCV)

According to this analysis the enlighten part of the crown (LCV) was correlated with total standing biomass (i.e. volume per hectare), the average DBH and the dominant height (i.e. the Site index) with was also connected to the volume of the shaded portion of the crown (SCV) and the total crown volume (TCV). Then concerning structural parameters, statistically significant and interesting correlations were found between SCV and the proportion of ground covered by canopy (COV), correlated with TCV too. Concerning PAR, just a negative correlation was found with TCV.

Discussion

Models to support forest management

The crown volume values calculated by means of the statistic models represents a step forwards to novel multivariate and multicriteria analysis. Even if small, substantial differences could be defined among models allowing the use of nonlinear equations, probably able to characterise the ecological processes more properly. 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; Di Biase et al. 2018; Pecchi et al. 2019). Simple multipliers obtained averaging raw data seems to be anachronistic and are not able to detect the variability of the analysed phenomena as well as to provide inferences on the output (Bayer et al. 2013). The difference between model-estimated and multiplier-estimated L_0 and r_{cb} values can be observed in Fig. 5 where the values predicted by the provided models have been plotted against those calculated with several multiplies ranging between 0.3 and 0.8 as proposed in literature (Pretzsch 2009). While the estimation for L_0 showed a small discrepancy with a value for *Pinus nigra* around 0.68, a pretty different pattern was observed for r_{cb} where the curvilinear shape was much more pronounced.

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. Tree crown architecture is essential for tree growth, impacting on biodiversity level on the ground, modelling the amount of light available for chemical decomposition of organic components and influencing the natural cycle of elements as well as decomposition of organic CO_2 stocked in the soil (Jakovljevic et al. 2009; Savi and Fares 2014). This is particularity true in artificial black pine stands, a dynamic system where biological processes play a fundamental role for future scenarios and ecological successions (Piermattei et al. 2012; Barbato et al. 2019). In this framework a reliable model to predict crown shape and value might open new possibilities, working as indicator of occurrence of biological processes. However, this tool would be influenced by many site-specific feature and, consequently, further attempts should be studied in order to parametrise different models in different conditions and species.

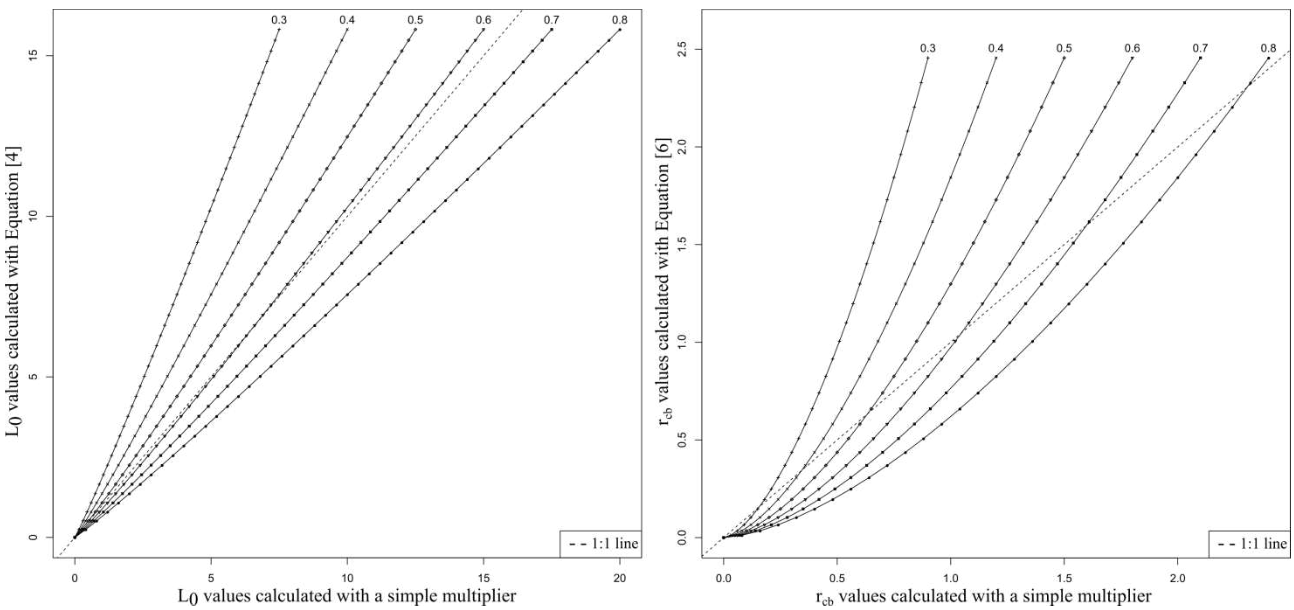

Figure 5 Estimated L_0 and r_{cb} values predicted by the models (y axis) against values obtained from a simple multiplier approach (x-axis)

A practical use of models: the SelPiBio LIFE project

A very important aspect is the evaluation of the effects of silvicultural treatments on the space occupied by the canopy in forest stands and how these, quantitatively and qualitatively, affects the photosynthetic capacity and the levels of competition. It is important to keep in mind how silvicultural interventions play a fundamental role in the characterization of the foliar mass of forest populations, going to affect the competitive relationships by modifying the social positions (rank) of the plants that remain standing, based on the spaces created and the resources ceded by plants that fall when cut. The models we built was the evaluated under the light of a thinning made under the SelPiBio project (www.selpibio.eu). There 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 in artificial black pine stands. For instance, a comparison between silvicultural treatment is proposed in Table 4 where the data coming from two different thinning systems on artificial black pine stands (Marchi et al. 2018) were compared using the here provided models. In each study area, 3 forest monitoring sectors were managed by selective thinning (3 ha in total, 9 plots per study area) and 3 forest monitoring sectors were managed by low thinning (3 ha in total, 9 plots per study area). In the selective thinning, 100 trees per hectare were selected from among the better formed and mechanically stable trees. During cutting, all crown competitors of target trees were harvested to increase their growth (positive selection). In the low thinning, only dominated, small or standing dead trees were harvested (negative selection) during in-field operations.

Table 4 Summary statistics of the effect of two different thinning methods (low and selective thinning) in two artificial black pine stands (Monte Amiata and Pratomagno) where the total crown volume removed was calculated with the models provided in this study

	Thinning type	**N trees per ha**	**Basal area**	**Biomass**	**Crown Vol**	**PAR**
AMIATA	Low thinning	-30.4%	-19.7%	-18.7%	-11.2%	+133%
	Selective thinning	-34.3%	-31.9%	-30.7%	-24.4%	+413%
PRATOMAGNO	Low thinning	-35.9%	-22.6%	-19.3%	-11.3%	+87%
	Selective thinning	-30.8%	-29.4%	-29.7%	-21.2%	+232%

When disentangling average values, data became even more interesting if analysed among ranks (Fig. 6). Most of the crown volume was allocated (as expected) in co-dominant and dominant trees, only removed with the crown thinning. Even if most of the current thinning schemes are aimed at evaluating / limiting 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). In this case the here provided model can support forest managers to estimate this parameter more easily and effectively at low cost

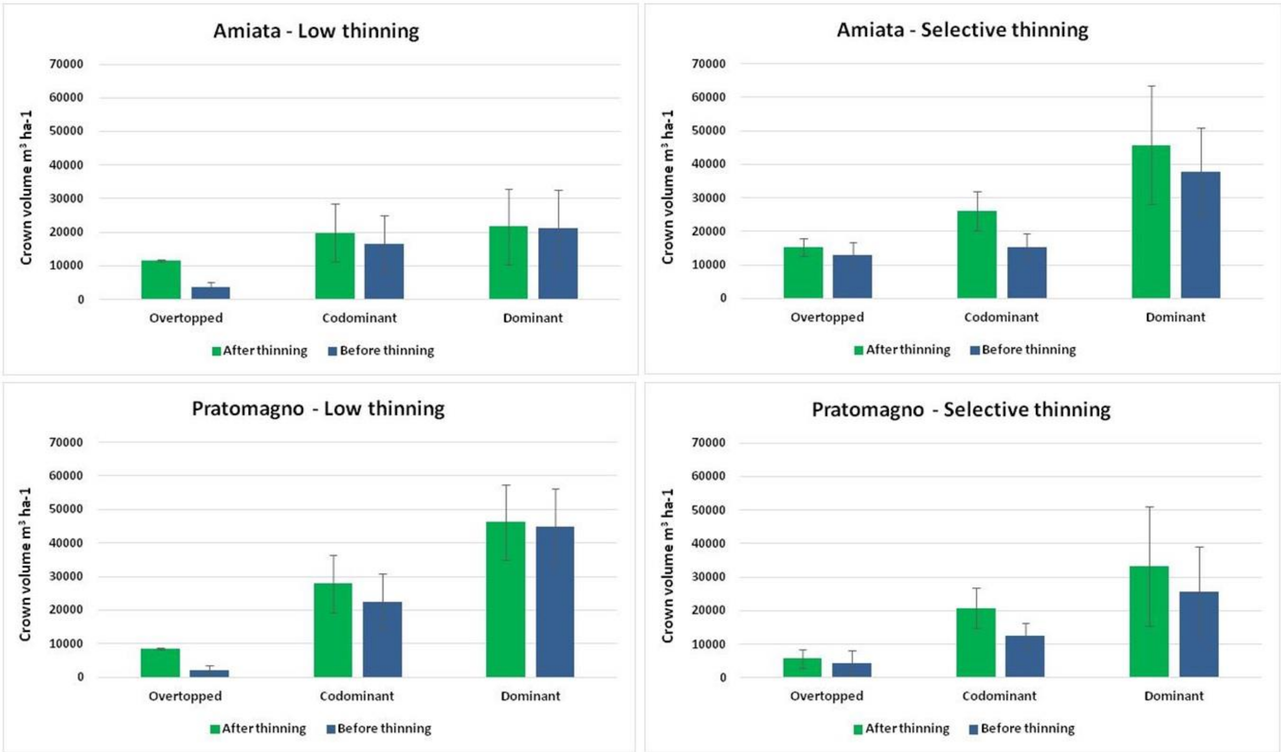

Figure 6 Crown volume removed across the social classes (ranks) in the SelPiBio study case

Conclusions

Statistical models such as growth models and process-based models can support forest managers and decision-makers to predict/hypothesize the most interesting trajectory for the managed stand. The models we proposed could be considered an additional tool to support the practical management of artificial black pine stands. The further shift towards increasingly mature stages of the pinewoods requires special attention to the evolution and renewal processes of these stands, particularly in the light of current climate change and the high vulnerability of these in relation to phytosanitary risks and fire that could threaten them, undermining their structure and stability. In this context 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.

Availability of data and materials

The dataset used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Ethics declarations

Ethics approval and consent to participate

Not applicable.

Competing interests

The authors declare that they have no competing interests.