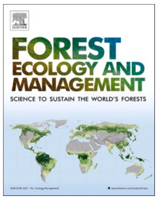
Forest Ecology and Management 523 (2022) 120490

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco



Optimizing quality wood production in chestnut (*Castanea sativa* Mill.) coppices

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ARTICLE INFO

Keywords:
Coppice with standards
Simple coppice
Productivity
Silviculture
Quality wood
Forest management

ABSTRACT

In the last decades, releasing standards have become a very common and in some cases even mandatory management options in coppice systems in Europe. As for the chestnut tree, a light demanding and fast-growing species, however, there is a lively debate and a lack of scientific evidences about the pros and cons of releasing standards, especially in stands devoted to quality wood production. In this paper we used nine chestnut coppice stands growing on similar site conditions - but differing in stool density and number of standard trees released - to analyze the effects of the stand structure (i.e., stool and standard density) on the growing performance in terms of diameter increment of the dominant shoots and overall basal area production. Simple coppicing (i.e., no standards release) confirmed to be the most suitable system to enable an initial full growing performance of a light-demanding species such as the chestnut. We thus recommend avoiding the release of standards in quality-wood chestnut coppices in order to allow the new shoots generation to develop undisturbed until the stage of the first thinning. The release of standards in chestnut coppices may however be appropriate in particular cases, such as in stands whose main aim is to protect against shallow landslides along steep slopes.

1. Introduction

Coppicing is among the most simple and ancient systems of managing woodlands (Matthews, 1991) and has been already described in detail since the Romans (i.e., De re rustica by Columella). In Europe coppicing is applied on about 16 % of the productive forest area (UN/ECE-FAO, 2000) and refers to native (e.g., *Quercus* L. spp., *Castanea sativa* Mill., *Carpinus betulus* L., *Ostrya carpinifolia* (Scop.), *Salix* L. spp., *Populus* L. spp., *Alnus* Mill. spp., and *Tilia* L. spp.) and introduced (*Robinia pseudacacia* L., *Eucaliptus* L'Hér. spp.) broadleaved woody species with high sprouting capacity (Jarman and Kofman, 2017).

Among existing coppice systems, two management approaches are the most used. Simple coppice, consisting in periodic (e.g. every 10 to 20 years) coppicing of the stools (i.e., living stump from where the shoots are resprouting) in order to produce even-aged, single-storey structures for poles or firewood production and coppice with standards, where at each felling a number of shoots (i.e., stem originated from a bud at the base of the stump) or trees originated from seed are kept for two or more rotations in order to form an overstory of oversized individuals (Jarman and Kofman, 2017).

Coppice with standards (Italian: *Ceduo sotto fustaia*; German: *Mittelwald*; French: *taillis sous futaie*) originally combined the coppice understory with an overstorey mainly composed by trees originated from seed (Zanzi Sulli and Di Pasquale, 1993). Nevertheless, including standards originating from selected shoots (Italian: *Matricine*; German: *Überhälter*; French: *balivaux*) and extending the rotation period represent an adaptive evolution of the coppice approach aimed at differentiating the timber products so as to meet the changing market needs (Manetti and Amorini, 2012). Besides increasing the size of the produced timber, releasing standards also aim at keeping mature individuals producing

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https://doi.org/10.1016/j.foreco.2022.120490
Received 27 June 2022; Received in revised form 12 August 2022; Accepted 17 August 2022

Table 1
Coppice area and coppice systems in selected European chestnut countries.

Country	Coppice area and systems[a]			Chestnut coppice			
	Area (ha)	Rotation (years)	Number of standards	Area (ha)	Rotation (years)	Number of standards	References
Italy	3,666,310	12–40	50–180	497,870	8–50	20–70	Manetti and Amorini (2012); D.L. (2018)
France	6,372,000	10–60	50–100	920,500	10–60	Only in poor quality sites	Bourgeois et al 2004
Spain	4,000,000	15–30	not defined	99,948	15–30	Only in high quality sites	Piqué et al. (2018)
Portugal	863,000	12–30	not defined	33,900	20–50	Not defined	Carvalho et al. (2018)
Switzerland	35,200	15–30	at present on chestnut only	23,700	15–30	None	Cueni et al. (2018); Swiss Federal Act on Forest SR 921.0
Greece	1,930,000	10–50	50–100	33,051	10–50	None, prohibited to prevent the blight infestation	Mallinis et al (2018)
England	24,000	10–50	50–100	18,788	10–50	None	Buckley and Howell (2004); Bartlett et al. (2018)

[a] source:Unrau et al. (2018).

seeds to replace exhausted and dying stools, assuring a permanent minimal soil cover, especially in the first post-coppicing years and enhancing the species mixture by favoring rare tree species (Buckley, 1992; Zanzi Sulli and Di Pasquale, 1993). Assuring on–site seed production was particularly important during the first decades of last century, when the coppice rotation time was kept very short (<10 years) because of the general wood shortage on the market (Fabbio, 2016). This has resulted in a long-lasting adaptive process combining local traditions with the evolving demand of timber products and the pressure of an increasing environmental awareness in the society. As a result, forest policies and guidelines on coppice management are very heterogeneous throughout Europe (Table 1) and poorly supported by scientific evidences (Manetti and Amorini, 2012).

The lack of a strong scientific confirmation for the suitability of releasing standards is markedly evident in pioneer-like, light demanding and fast-growing chestnut coppices (Manetti et al. 2020), which cover 1.48 million of hectares and represent an important economic resource mainly in France, Italy, Spain, Greece, Switzerland, and England (e.g., Conedera et al., 2004; Bourgeois et al., 2004; Menéndez-Miguélez et al., 2013). When looking at the historical forest literature, simple coppicing has long been considered as a recommended treatment for the chestnut tree. For the Italian Peninsula this was for instance the case by Cotta (1918) and Piccioli (1922), who further suggested the plantation of new chestnut trees or the rooting of shoots to renew exhausted or dead stools. For France, not only in ancient literature the practice of standards release has been explicitly discouraged (e.g., Blin, 1904; Tricaud, 1913), but also recent specific silvicultural treatises consider the *balivage* in chestnut coppices as an unsuited option (Bourgeois et al., 2004). Similarly, in Switzerland (e.g., Merz, 1919) or England (e.g., Braden and Russell 2001), where no specific recommendations of releasing standards in chestnut coppices exist to date, their presence may have been encouraged in particular cases to preserve biodiversity (e.g., Buckley and Howell, 2004, Bartlett et al., 2018). In Spain the release of standards in chestnut coppices has been limited to very good sites to produce large dimension timber (Piqué et al., 2018), whereas in Greece the tradition of managing chestnut coppice with standards has been suspended in the 1990s to prevent the spread of the chestnut blight (Mallinis et al., 2018). Furthermore, recent studies have shown that the capacity of long rotation chestnut coppices under standard climatic conditions to produce viable seeds and to subsequent initiate the gamic regeneration of stand does not pose a problem (Conedera et al., 2006; Marcolin et al., 2020).

Table 2
Current prescriptions on chestnut coppice management in the seven most important chestnut regions of Italy.

Region	release (year)	Rotation period (yrs)		Standards		Maximal extension (ha)
		Min	Max	N min	Spatial distribution	
Piemonte	2011	10	not defined	–	clustered[a]	5
Toscana	2003	8	50	30	uniform	20
Liguria	1999	12	not defined	60[b]	uniform or clustered	not defined
Lombardia	2007	15	not defined	50	uniform or clustered (10 max)	10
Calabria	2011	12	24[c]	30[d]	uniform or clustered	10
Lazio	2005	14	35	30	uniform or clustered	20
Campania	2003	12	not defined	30	uniform or clustered	not defined

[a] at least 10 standards per cluster, maximal extension = 200 m^2 per cluster, distance among cluster at least 1.5 × max height.
[b] standards release not mandatory.
[c] further extension of the rotation period possible with authorization only.
[d] standards release not mandatory only in case of a diffuse presence and high impact of the chestnut blight.

In Italy, the increasing demand of energy wood at the beginning of last century caused a progressive and general reduction of the rotation period and the depletion of coppice woodlands. As a reaction, the debate about the need of releasing standards in coppice stands became a polarizing topic, regardless of the tree species concerned (Zanzi Sulli and Di Pasquale, 1993). Despite the strong recommendations to avoid a high number of standards in chestnut coppices (e.g., 20 to 50 n/ha, Remondino, 1926), the new societal demands for forest conservation as a good of primary landscape and environmental interest since the last post-war period (Manetti and Amorini, 2012) did not allow specific exceptions for the chestnut tree. Recently, present forest regulations concerning chestnut coppices in Italy have been increasingly criticized (e.g., Zanzi Sulli, 1995; Fiorucci, 2009; Manetti and Amorini, 2012, Manetti et al., 2020), as they only partially consider the ecological and silvicultural characteristics of the species and still report tradition-driven prescriptions with substantial differences among regions (Table 2). This highly contrasts with present trends in market demand for chestnut timber requiring quality wood, which may be produced in chestnut coppices by assuring a regular and substantial growth rate to the trees (Conedera et al., 2004; Manetti et al., 2016). A sustained growth reduces both the time needed for the trees to reach the target-size and minimizes the risk of ring-shake failures in the produced timber (Fonti and Sell, 2003; Manetti et al., 2016).

In order to contribute to the scientific debate about the best suited approach to produce quality wood from chestnut coppice, we used here nine experimental plots growing on similar site conditions but differing in stool density and number of standard trees released to analyze the effects of the stand structure on the growing performance in terms of dominant tree size and overall basal area production. We hypothesize in particular that releasing standards in chestnut coppices devoted to the quality wood production has a negative impact on the overall stand production.

2. Materials and methods

2.1. Study area and experimental design

The research was carried out at the Monte Amiata in Tuscany (Central Italy), in a forest district characterized by a relevant presence of chestnut (*Castanea sativa* Mill.) coppices for wood production. Chestnut stands extend over 3,534 ha and are located between 800 and 1200 m asl. The silvicultural system differs as a function of property: short rotation periods (<20 years), no thinning as well as a high number of standards (up to 60–80 per hectare, Fig. 1A) in private forests (i.e., 87 % of the chestnut forest area) and longer rotations (up to 25–30 years), thinning from below at mid-rotation, and the release of about 30–40 standards per hectare (Fig. 1B) in the public property (D.R.E.Am. Italia, 2015).

Most soils consist of deep, well drained, coarse loamy siliceous and mesic Andic Dystrudepts, (unit GUA1 – http:// sit.lamma.rete.toscana.it/websuoli/) on a trachyte bedrock. The climate is upper-Mediterranean with an average annual rainfall of 915 mm (325 mm in autumn; 266 mm in winter, and 131 mm in summer) and a mean annual temperature of 11.4 °C (meteorological station at Piancastagnaio, 450 m asl, period 1990–2010).

The experimental design includes four pure chestnut simple coppicing (SC) plots (Fig. 1C) aged between 8 and 16 years and issued from a previous research started in 2000 (Manetti and Amorini, 2012) and five coppices with standards (i.e., standard release - SR, Fig. 1D) of the same age range and with different standard densities, selected on similar site conditions in the surroundings (Table 3). We ended up with 9 plots located within a radius of 5 km at Piancastagnaio (WGS84 lat. 42.87007 N, long. 11.66672 E; Fig. 2). The plots are rectangular in shape (side lengths ratio of 1:2) and their size varies between 600 and 800 m^2 in order to assure homogeneous site conditions. Stool density ranges between 450 and 800n·ha^{-1}, whereas the released standards in the SR ranges from 25 to 113 n·ha^{-1} (Table 3).

2.2. Data collection and pre-processing

In spring 2018, all stools, standards, and trees originated from seed growing on the plots were mapped (i.e., georeferenced), labeled and assessed in terms of tree species, social position (A = dominant, B = intermediated, C = dominated), total height and crown radii along four cardinal points (north, east, south, west). Type (shoot, standard, or tree originated from seed) and diameter at breast height (DBH) were then registered for each individual with DBH ≥ 3 cm, whereas single shoots were additionally referred to each stool.

Distances among stools and distances to the nearest standard tree inside the plot have been calculated in a GIS environment using ArcGIS 10.8 (ESRI, Redlands, California, USA), whereas for stools at the plot edge the distance to the next competing stool outside the plot has been additionally measured in the field. We also assigned to each stool a distance from the competing stools (d_stools) by calculating the average distance of the three closest stools (Nosenzo et al., 1996).

In order to check for site conditions equivalence and to make data comparable among plots of different ages, we standardized the growth data of the chestnut shoots to the values at the age of ten years using the growing curves for chestnut coppices provided by Bourgeois et al., 2004. Considering the juvenile phase of the coppices investigated and assuming a certain linearity in the height growth of the dominant shoot (Manetti et al., 2001; Lemaire, 2008a), we used the average increment curves proposed by Bourgois et al. (2004) to rescale the I_G at ten years starting from the I_G at eight and sixteen years, respectively. Similarly, we rescaled the I_Ddom of each stool aged of eight and sixteen years, respectively. The similarity among the standardized heights of the dominant shoots (and thus of the site growing conditions; Lemaire, 2008a) was then tested with the non-parametric Kruskal-Wallis test ($p < 0.05$). Fig. 3 summarizes the workflow and visualizes the single pre-processing steps we performed before entering the analysis.

Fig. 1. Glimpses of different chestnut coppices: A) one-year coppice with a high number of standard release; B) 25-year coppice thinned from below and a low number of standard release; C) simple coppice (without standard release); D) Coppice with standards.

Table 3
Main site and stand characteristics of the selected experimental plots.

plot ID	1	2	3	4	5	6	7	8	9
management	SC	SC	SC	SC	ST	ST	ST	ST	ST
coppice age (years)	8	10	10	16	10	10	8	16	16
area (m^2)	600	800	600	800	800	800	600	800	800
altitude (m asl)	1000	870	870	1000	870	870	1000	1000	1000
aspect	E	S-E	S-E	E	S-E	S-E	E	E	E
slope (%)	0	7	9	0	8	9	0	0	0
H_{dom} (m)	9.8	12.0	11.8	16.0	12.2	12.7	11.2	17.6	17.5
N_Std (n ha^{-1})	0	0	0	0	25	50	100	113	100
N_Stool (n ha^{-1})	650	550	800	575	725	713	725	625	450
N_Shoot (n ha^{-1})	7338	5850	6500	4038	5875	5163	6725	3000	3300
Shoot/Stool	11.3	10.6	8.1	7.0	8.1	7.2	9.3	4.8	7.3
BA_Std (m^2 ha^{-1})	0.00	0.00	0.00	0.00	3.98	8.05	10.90	18.80	12.49
BA_Shoot (m^2 ha^{-1})	23.95	28.62	27.50	38.09	25.00	23.13	17.97	22.60	24.50
BA_Tot (m^2 ha^{-1})	23.95	28.62	27.50	38.09	28.98	31.18	28.87	41.41	36.98
CA_Std (m^2)	0	0	0	0	30.4 (0.7)	30.7 (8.7)	20.2 (3.9)	48.9 (10.0)	40.1 (4.7)
CA_Stool (m^2)	20.8 (1.4)	21.3 (1.6)	15.9 (1.5)	19.6 (1.6)	12.9 (1.3)	14.9 (1.3)	14.7 (1.4)	11.2 (1.4)	19.5 (2.1)

H_{dom} = dominant height of the coppice component; N_Std = standard density; N_Stool = stool density; N_Shoot = number of shoots per hectare; Shoot/Stool = number of shoots per stool; BA_Std = basal area of standards; BA_Shoot = basal area of shoots; BA_Tot = total basal area per hectare; CA_Std = mean crown area of the standards (±standard error); CA_Stool = mean crown area of the stools (±standard error).

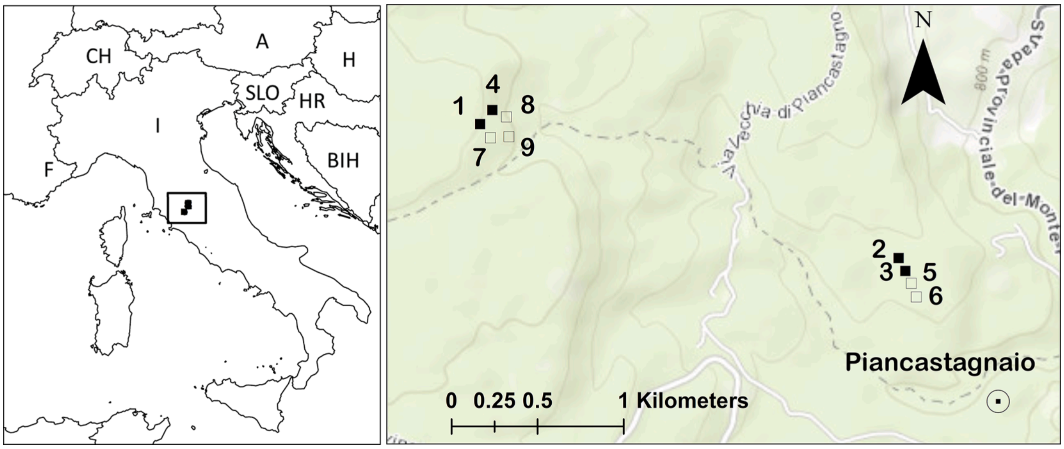

Fig. 2. Study area (black rectangle in the map at the left) and geographical distribution of the different experimental plots (detailed map on the right). Black squares = simple coppice; white squares = coppice with standards. Numbers correspond to the Plot-ID in Table 3.

2.3. Data analysis

The data analysis has been performed in different steps (see supplementary materials 1 for details).

In the first step, we tested the effect of different coppice management (SC vs SR), stand age, structure of the coppice component (stool social class [coppice_social], stool crown radius [R_c], mean distance between stools [d_stools], number of shoots per stool [shoots]), structure of the standards component (distance [d_std], basal area [G_std], height [H_std], and crown radius [R_std] of the nearest standard tree) and their interactions on the dominant diameter of each stool (Ddom) by fitting generalized linear models (GLMs). Since the canopy size of the stool (Rc) is age-dependent, age was assumed for GLM to be “nested” within Rc. GLMs were applied with a forward stepwise selection to retain those variables only showing a significant effect ($p < 0.05$) on Ddom when added to the model. Considering that in the SR plots the maximal distance of a stool to the next standard (i.e., *d_std*) is 19.5 m, we assigned a set of conventional theoretical values in SC plots (i.e., d_std = 20 m, G_std = 0, H_sdt = 0 m) in order to be able to fully analyze the database. The best fitting model in terms of highest adjusted R^2 and lowest mean absolute error (MAE) of residuals was then selected. Durbin-Watson statistic was used to test the residuals for any significant correlation based on the order in which they occurred in the dataset. Outliers on data and heteroscedasticity on residuals were checked.

In the second step, among the explanatory variables retained by the GLM, we selected those that can be influenced by a silvicultural management of the stands to fit two Multiple Regressions models in order to test their impact on the first ten years of development of the coppice component in terms of i) the increment rate of basal area per hectare (I_G) and ii) the diameter increment rate of the dominant shoots (I_Ddom).

We then used the regression models to simulate the stand growth at ten years since coppicing and to detect patterns or thresholds in the stand structure allowing to optimize quality wood production (i.e., highest possible number of dominant shoots with a good performance in terms of diameter increment). To this purpose, we first simulated the simple coppice and then progressively reduced the space available for chestnut stools by subtracting the surface occupied by the corresponding number of released standard trees.

Explanatory variables retained by GLM were checked for Spearman correlations (r_s, $p < 0.05$) with the growth parameters Hdom and Ddom.

Differences between the two management options (SR, SC) in terms of stools arrangement in social classes have been checked by a chi-squared (χ^2) test ($p < 0.05$).

Univariate and model analyses were performed using Statgraphics Centurion (StatPoint Technologies Inc., Warrenton, VA, USA).

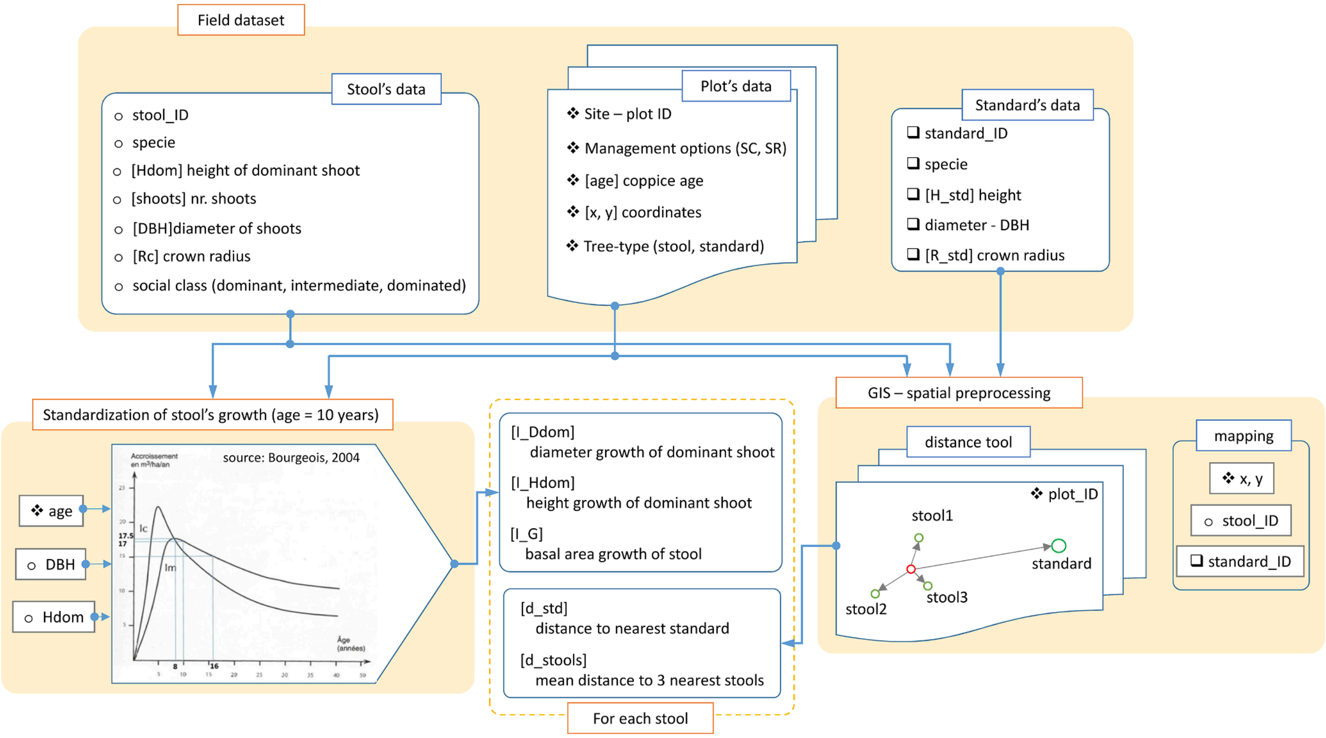

Fig. 3. Workflow from the field data collection to the data preprocessing.

3. Results

3.1. Sites equivalence and stand structures

Standardized data at ten years since coppicing confirmed the similarity of the experimental plots in terms of height growth rate of the dominant shoots, which results in an average of ca. one meter per year and does not differ among sites ($p > 0.05$, Kruskal-Wallis test; $n = 406$ stools).

Even though standard trees are excluded from the calculation, there are significant differences between simple coppicing (SC) and coppice with standards (SR) ($p < 0.05$, Kruskal-Wallis test on $n = 406$ stools) regarding the annual increment in basal area of the dominant shoots, ($I\_G = 40.5$ +/- 35.6 $cm^2 \cdot stool^{-1}$ in SC vs 31.4 +/- 28.9 $cm^2 \cdot stool^{-1}$ in SR, respectively) as well as in terms of canopy radius of stool crowns (Rc = 2.3 +/- 0.82 m in SC vs 1.9 +/- 0.78 m in SR, respectively) (Table 4).

Significant differences between the two management options could also be highlighted in terms of stools arrangement in social classes ($\chi^2 = 44.22$, $p < 0.01$), with a higher proportion of dominant ones in the SC plots (Table 4).

3.2. Drivers of shoot growth

Table 5 reports the overall GLM scores ($F = 45.3$, $p < 0.001$, $R^2 = 0.67$) and the retained explanatory variables for the diameter growth rate of the dominant shoot at stool level. In addition to the expected factors *age* and *social* classes, the final model retained *d_stools*, *d_std* and *Rc* as parameters significantly affecting the Ddom of stools (Table 5). On the contrary, no variables referring to the size of the standard trees (G_std, H_std, R_std), or significant interactions between variables were retained ($p > 0.05$). Spearman correlations revealed strong relationships between Ddom and Hdom ($r_s = 0.78$) as well as between Ddom and Rc ($r_s = 0.63$), whereas positive correlations were confirmed between Rc and d_stools ($r_s = 0.37$).

Table 4
Stand parameters standardized at the age of ten years post-coppicing according to the management type.

parameter	unit	simple coppice (n = 171)		coppice with standard (n = 235)		significance tests
		mean	±SD / [min, max]	mean	±SD / [min, max]	
I_G	($cm^2 \cdot stool^{-1}$)	40.5	± 35.6	31.4	± 28.9	$p < 0.05^1$
I_Ddom	($cm \cdot year^{-1}$)	0.87	± 0.33	0.81	± 0.27	*ns*^{1}
I_Hdom	($m \cdot year^{-1}$)	1.04	± 0.21	1.1	± 0.17	*ns*^{1}
d_stools	(m)	3.0	[0.9, 5.8]	2.9	[1.2, 6.7]	*ns*^{1}
d_std	(m)	–	–	5.6	[0.5, 19.5]	–
dominant	(%)	70		39		$p < 0.01^2$
intermediate	(%)	12		30		
dominated	(%)	18		31		

I_G = increment rate in stool basal area.
I_Ddom = diameter increment rate of the dominant shoot.
I_Hdom = height increment rate of dominant shoot.
d_stools = mean distance of each stool to the three nearest ones.
d_std = distance of each stool to the nearest standard-tree.
dominant, intermediate and dominated refer to the social arrangement of the stools.
significance tests = $^{1)}$ Kruskal-Wallis test; $^{2)}$ χ^2 test.

Table 5
GLM results for the dominant diameter increment of each considered stools (I_Ddom). Statistics of the final model (top) and estimated coefficients of the retained explanatory variables (bottom).

Model summary	*Sum of Squares*	*Df*	*Mean Square*	*F-Ratio*	*P value*
Model	3420.9	19	180.05	45.37	< 0.001
Residual	1531.7	386	3.96		
Total	4952.7	405			
adjusted R^2	0.67				
Mean Absolute Error	1.5				
Durbin-Watson	1.94 ($p > 0.05$)				
Observations	406				

Variables retained		*Estimated coeff.*	*Std error*	*F ratio ($p < 0.01$)*
age	8y	2.8	0.62	17.3
	10y	2.5	0.84	
	16y	0.29	0.08	
coppice	SR	10.8	1.1	19.6
	SC	12.4	0.9	
d_stools		0.41	0.03	5.3
d_std		0.56	0.11	18.8
Rc	dominant	2.79	0.18	107.8
	intermediate	2.36	0.26	
	dominated	1.7	0.41	

age (factor) = 8, 10, 16 years; coppice (factor) = SC, SR; d_stools = distance between stools; d_std = distance to the nearest standard-tree; Rc = mean radius of stool canopy; social classes of stools = dominant, intermediate, dominated.

The final model was checked for homoscedastic and normally distributed residuals and the Durbin-Watson statistic showed no indication of serial autocorrelation in the residuals at the 95.0 % confidence ($p > 0.05$).

3.3. *Stand growth simulations*

Among all variables retained by the GLM, we selected only *d_stools* and *d_std* for the regression model on the ten years standardized basal area (I_G) and dominant diameter (I_Ddom) increments at stool level. By doing so, we considered the most controllable parameters by silvicultural interventions, although with an expected reduction of the resulting R^2 compared to the full GLM. Nonetheless, the regression models highlighted a strong control by the explanatory variables *d_stools* and *d_std* in coppice with standards and of *d_stools* in simple coppicing, respectively (Table 5).

Considering these results, we started simulating the influence of stool density and the release of standard trees on the production in terms of average basal area per hectare (BA) and diameter increment of dominant shoot (I_Ddom) for the chestnut coppices at ten years of age, growing on similar site conditions as the analyzed ones. We first calculated the increment rates for regularly distributed simple coppice stools of different density, i.e. ranging from 200 to 1000 individuals per hectare (Fig. 4). In addition to the simulated data, we reported the social arrangement of the stools for three categories of stool densities (stool densities < 400 n·ha^{-1}, $400 <$ stool densities < 600 n·ha^{-1}, stool densities > 600 n·ha^{-1}). For stool densities between 400 and 600, the average increment in diameter remains in the favorable range close to 1 cm per year (i.e., the yearly increment threshold to minimize the risk of ring shake; Fonti and Sell, 2003) and the overall basal area production at ten years ranges between 14 and 17 m^2·ha^{-1}. When the stand density exceeds 600 n·ha^{-1}, the average increase in diameter markedly drop below 1 cm per year, whereas for stools density below the threshold of 400 n·ha^{-1} the basal area linearly decreases below 14 m^2·ha^{-1}. Similarly, the proportion of dominant stools hardly exceeds 50 % of the total for stool densities > 600 n·ha^{-1} (*d_stools* < 4 m), with an increasing trend (60 % with ca. 500 n·ha^{-1}) up to 70 % for stool densities < 400 n·ha^{-1} (*d_stools* > 5 m) (Fig. 4).

Fig. 5 reports the effect of including an increasing number of standard trees (between 5 and 30 standard trees·ha^{-1}) in the simulations by modulating the resulting distance from the coppice stools (*d_std*) at 10, 8,

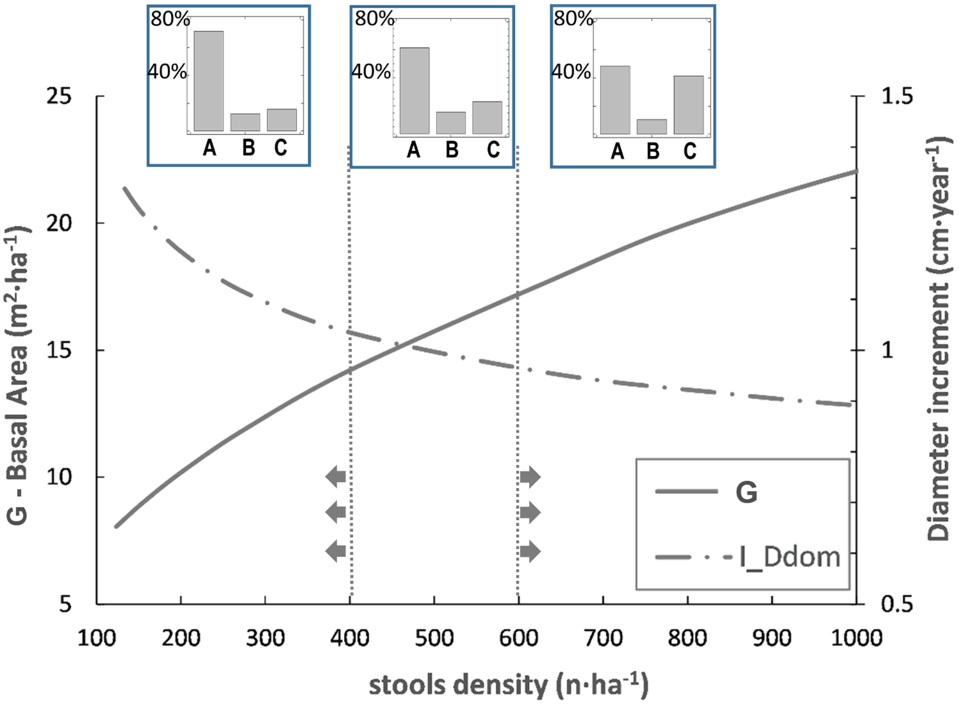

Fig. 4. Simulated average basal area per hectare (G) and diameter increments of the dominant shoots (I_Ddom) at 10 years-old in simple coppices (SC) as a function of the stool density ranging (i.e, from 200 to 1000 n·ha^{-1}). Social classes arrangements (A = dominant, B = intermediate, C = dominated) refer to three categories of stool densities ($<$400 n·ha^{-1}; 400–600 n·ha^{-1}, $>$ 600 n·ha^{-1}). G = I_G × 10 × stools density, with stools density = 10000 × (d_stools)$^{-2}$.

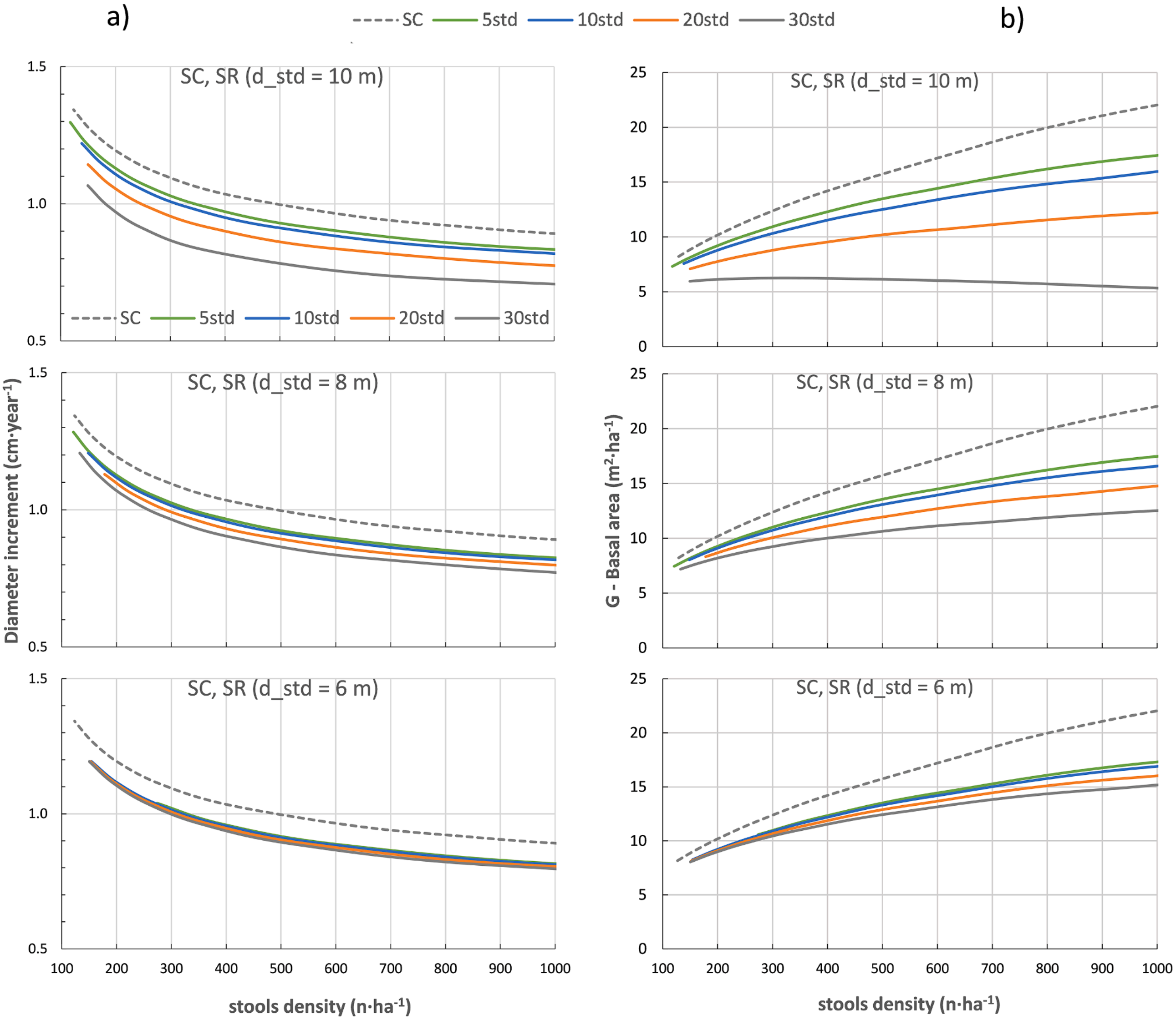

Fig. 5. Average increment in diameter of the dominant shoots (a) and in basal area per hectare (b) at 10 years since coppicing and as function of the density of the released standards (from 5 to 30 n·ha^{-1}) and different distances to the next standard (6 m, 8 m, 10 m).

and 6 m, respectively. The diameter increments show a systematic drop with respect to the simple coppice as a consequence of the increasing number of standards and the related decreasing distance to the next standard (Fig. 5a). The resulting penalty becomes evident also in terms of basal area of the whole coppice component (Fig. 5b).

4. Discussion

In this paper, we analysed the effect of releasing standards trees in chestnut coppices devoted to quality timber production. We focused in particular on chestnut coppices at the 10 year-development stage, which usually corresponds to the beginning of the between-stools competition and for the forest managers to the need of thinning in order to assure an optimal growing rate of the dominant, quality-bearing shoots (Manetti et al., 2006; Manetti et al., 2016). Despite existing methodological constraints and limitations when standardizing only the data of the coppice component at ten years since coppicing - this does not apply to the data of the standard trees - in order to make results comparable among plots, the outcomes give important and consistent ecological and silvicultural indications. As highlighted by the modelling approach, the mere presence of standard trees shows a significant influence on the growth of the coppice component regardless of the standards size and their crown expansion.

From an ecological point of view, the chestnut tree proved to privilege or even need full light conditions for assuring high growth rates for quality wood production (Lemaire, 2008a; Conedera et al., 2016). From a silvicultural point of view, this is best and automatically warranted by the simple coppice system. As a result, our modelling approach confirms the positive relationship between a full canopy development when stools dispose of enough space and a corresponding high diameter increment of the shoots (Mitchell and Popovich, 1997; Marcolin et al., 2020). Moreover, a sound regulation of the distance among stools (i.e., stool density) along with the complete removal of the mature generation when coppicing is performed, allow the stand to perform better also in terms of percentage of dominant stools (Manetti and Amorini, 2012). Distance among stools and between stools and standard trees in particular not only influence the diameter and vertical growth rate of the shoots (Marcolin et al., 2020), but additionally impact highly their morphological shape, vitality, and phytosanitary conditions (Piussi, 2006; Cantiani et al., 2006). A broad choice of well-shaped, high performing, and spatially well-distributed candidates is thus the best prerequisite to allow a highly qualitative and value-bearing selection of stems for the final product (Manetti et al., 2010).

Furthermore, our results clearly show the need for forest managers to optimize between two contrasting trends: assuring a sustained diameter increment rate of the dominant target shoots avoiding too high stand densities (i.e., overall number of stools and standard trees) without excessively decreasing the overall biomass productivity due to high distances among stools (Menéndez-Miguélez et al., 2014). Finding a suitable trade-off between these two contrasting trends allows not only to optimize the diameter increment rates of the candidates but also to assure high quality in terms of trunk shape (e.g., avoiding the curvy growth of the basal part of the shoot and unilateral crown formation) (Menéndez-Miguélez et al., 2016). Low stool densities may also fail to assure a rapid soil protection (Manetti et al., 2001, Giudici and Zingg, 2005), implying the lack of natural pruning of the lower branches, post-thinning epicormic reactions of the dominant shoots (Meier et al. 2012), and the colonisation of the stand by undesired pioneer woody species, including invasive neophytes such as *Ailanthus altissima* (Mill.) Swingle or *Robinia pseudoacacia* L. (Radtke et al., 2013). Focusing on the specific site conditions of our study cases, a stool density ranging between 400 and 600 n·ha^{-1} resulted to be optimal to assure a sustained diameter increment allowing to reduce the ringshake risk (Fonti and Sell, 2003; Cousseau and Lemaire, 2008) while ensuring good production. Targeting such optimal stool density additionally allows to reduce the thinning cycles until the final harvest of the coppice stand (Lemaire, 2008b).

Our results clearly demonstrated the detrimental effect of any standard release within the coppice stand on both the diameter increment rate of the chestnut shoots and the overall biomass production. Assuming an optimal stool density of 500 n·ha^{-1} and a distance of 10 m to the next standard, the overall productivity of the coppice decreases by 12 % with 5 standards only and by 55 % with 30 standards per hectare. Similarly, if the distance to the next standard is reduced to six meters, the productivity reduces of ca 20–30 %, almost regardless of the number of standards released. Furthermore, standards not only depress the growth but also reduce the shoots quality of the stools in the surroundings, making their release in stands aimed at quality wood production highly unsuitable. In case of long rotation coppices, pre-coppicing shoots are masting every year (Conedera et al., 2006), assuring thus the seed production and making the release of standards for the gamic regeneration aimed at replacing exhausted stools unnecessary.

5. Conclusions

In this contribution we demonstrate and discuss the uselessness of releasing standards in chestnut coppices devoted to quality wood production. Simple coppice confirms to be the most suitable system for a light-demanding species such as the chestnut tree as well as an easy-to-handle management option due to the lack of existing constraints in defining species, number, age and location of releasing standards. We thus recommend avoiding the release of standards in quality wood chestnut coppices in order to assure enough light and space to the new shoots generation, allowing them to develop undisturbed until the stage of the first thinning, which roughly corresponds to the first ten years ca. since coppicing, depending on the site productivity.

The release of standards may however be appropriate also in chestnut coppices. This may be the case when other high value tree species such as deciduous oaks (*Quercus* L. spp.), walnut (*Juglans regia* L.), cherry (*Prunus avium* L.) or sporadic tree species, such as the wild service tree (*Sorbus torminalis* (L.) Crantz) or the service tree (*Sorbus domestica* L.) are present and may be considered for quality wood production (Fabbio, 2016; Manetti et al., 2016). This may be further the case of protection forests against shallow landslides located along steep slopes, where the presence of the root system of the released standards may be of paramount importance during root renewal of the coppiced chestnut stools (Dazio et al., 2018). Finally, the release of a group of standards for scenic and landscape purposes may be suited in particular cases (Del Favero et al., 2015).

CRediT authorship contribution statement

Maria Chiara Manetti: Conceptualization, Data curation, Methodology, Project administration, Resources, Writing – review & editing, Supervision. **Marco Conedera:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Francesco Pelleri:** Data curation, Methodology, Investigation. **Piergiuseppe Montini:** Data curation, Investigation. **Alberto Maltoni:** Data curation, Investigation. **Barbara Mariotti:** Data curation, Investigation. **Mario Pividori:** Conceptualization, Methodology, Validation. **Enrico Marcolin:** Data curation, Formal analysis, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2022.120490.

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