ISHS Acta Horticulturae 1400: VII International Chestnut Symposium

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Authors: M.S. Patrício, L.F. Nunes
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DOI: 10.17660/ActaHortic.2024.1400.41

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The original publication is available at:

https://www.actahort.org/books/1400/

How to cite this article?

Patrício, M.S. and Nunes, L.F. (2024). Comparative growth and yield performance of sweet chestnut in high-forest and coppice systems in young plantations. Acta Hortic. 1400, 341-348. DOI: 10.17660/ActaHortic.2024.1400.41
https://doi.org/10.17660/ActaHortic.2024.1400.41

Comparative growth and yield performance of sweet chestnut in high-forest and coppice systems in young plantations

M.S. Patrício[1,2*] and L.F. Nunes[1,2]
[1]Centro de Investigação de Montanha (CIMO), Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal
[2]Laboratório Associado para a Sustentabilidade e Tecnologia em Regiões de Montanha (SusTEC),
* e-mail: sampat@ipb.pt

Abstract

We compare growth and yield of sweet chestnut in coppice and high-forest systems up to 24 years of age in Northern Portugal. In the coppice, data from 4 permanent plots submitted to different management models for small (P1), medium (P2) and large (P4) diameters, including a plot without intervention (P3), were used. Management model in P4 (1 shoot at the end of rotation) is converging to a similar product as high-forest over time. Site index (SI) for the coppice is 15 m of dominant height (hdom) at 20 years. The same SI was used when selecting data from permanent plots in high-forest for the comparison. Individual-tree equations previously developed were used to obtain stem volumes. Biomass of stem was obtained from volume using wood density. Results show that coppice for similar ages and SI, produces more stem volume per hectare than high-forest in any situation up to 24 years. At this age, height of the mean tree (hg) and hdom are lesser in the high-forest than in the coppice's management model with similar target (P4). In contrast, diameter of the mean tree (dg) and dominant diameter (ddom) are similar in both systems. Results also show that P4 in coppice system produced more 100 m^3 ha^{-1} of stem volume than the high-forest at age 24. However, mean annual increment (MAI) in stem volume in high-forest is still increasing as opposed to the coppice. Thus, coppice system produces more biomass in young ages than high-forest (MAI in biomass: 9 t ha^{-1} $year^{-1}$ against almost 4 t ha^{-1} $year^{-1}$, respectively). Managing coppice for a final target similar to high-forest introduces flexibility in sylviculture, allowing both high amount of biomass production in young stages, and long-life products at the end of rotation.

Keywords: *Castanea sativa* Mill., volume, biomass, high-forest, coppice, growth and yield

INTRODUCTION

The sweet chestnut (*Castanea sativa* Mill.) covers more than 2.5 million ha of forest area in Europe, most of them in the Mediterranean and Sub-Mediterranean areas (Conedera et al., 2021). These regions exhibit a climate characterized by mean annual temperatures ranging between 8 and 15 °C and minimum annual precipitation between 600 and 800 mm. Most of the area is concentrated in a few countries (France, Italy, followed by Spain, Portugal, and Switzerland) with a long tradition of chestnut cultivation (Conedera et al., 2004, 2016).

In Portugal, sweet chestnut (henceforth chestnut) can be found mostly in inland mountain areas in the North and Center of the country (Patrício et al., 2022). The area covered by the species is estimated to be > 48,000 ha (ICNF, 2015), including both orchards and forest woodlands. In forest woodlands, chestnut has been managed for wood production using both coppice and high-forest sylviculture systems. The demand for high-quality timber of broadleaf species has been increasing over time. High-quality chestnut timber is rare in Portugal but has a long tradition and market preference when available (Patrício et al., 2020).

The coppice is a very flexible system producing wood of several calibers adapting to the demands of the market. It is estimated that coppices share at least 10 percent of the total area of chestnut in Portugal (Patrício, 1996; Monteiro and Patrício, 1996). Traditionally, coppice played a major role in the production of small caliber roundwood mainly for poles, basketry, casks and other utensils used in agriculture, namely in the cultivation of vineyards and wine production. Over time, extensive areas of healthy coppices became unmanaged or managed without a technical or economic purpose, and are sometimes abandoned since the market does not have a preference for chestnut stems of small diameters. Their use for bioenergy does not seem to be a main option for landowners due to high harvest costs and low market prices (Patrício et al., 2020). In line with the ideas proposed by other authors (Bourgeois, 1987; Amorini et al., 2000; Cutini, 2001), new silvicultural management models, have been under experimentation in North Portugal since the mid-1990s. These models are based on the extent of rotation and periodic thinning, adapted to local edaphoclimatic conditions (Patrício, 1996; Monteiro and Patrício, 1996; Patrício et al., 2005; Patrício et al. 2020). The primary objective is to demonstrate to landowners that converting coppices into more valuable roundwood production and implementing multipurpose forestry can enhance profitability. By maximizing the utilization of harvested wood for long-lived products and allocating only the remaining proportion for bioenergy purposes, the mitigation of greenhouse gas (GHG) emissions can be increased (Birdsey et al., 2018).

High-forest has the potential to produce high-quality timber in fertile forest sites when proper sylvicultural management is applied (Clark et al., 2023). Patrício (2006) studied the productive potential of high-forest chestnut, focusing on the only known mature stands in northern Portugal. It is estimated that almost 10,000 ha of young plantations were established in the Bragança region, NE Portugal, between 1994 and 2000, supported by funds from the Community Support Frameworks (Patrício and Nunes, 2017; Patrício et al., 2022). Since the early 2000s, management models have been implemented in these young stands to demonstrate their potential for valuable timber production (Patrício, 2006).

Comparing the growth patterns of coppice and high-forest systems during the juvenile phase is essential, as coppice shows higher initial productivity but faces limited market demand for small-sized chestnut material. Exploring management alternatives to enhance long-term rotation and utilize juvenile biomass can incentivize the recovery of abandoned areas and improve the quality and value of chestnut timber for long-lived products for a more sustainable management.

The main aim of this work is to compare growth and yield of young chestnut stands in coppice and high-forest regimes in Northern Portugal. This comparison is based on data of field measurements ranging from 7 to 24 years of age. We aim to explore evidence that by implementing new management models as alternatives to traditional approaches, it is possible to enhance the quality, diversity, and value of the final products. This, in turn, can lead to increased benefits at economic, ecological, and environmental levels.

MATERIALS AND METHODS

Study area and data

For the coppice system, data on the growth of chestnut were collected from a trial located in *Serra da Padrela* (Figure 1), Northeast of Portugal was used. General characteristics of the site can be found in Patrício et al. (2020). The trial consists of four permanent research plots, each covering an area of about 1000 m^2. These plots were established in an even-aged coppice with 2-years-old shoots in 1994. This coppice was formed after clear-cutting a 50 year-old high-forest chestnut stand for timber harvesting. The site index (SI45) of the high-forest stand was estimated to be 24 m, determined using the equation developed by Patrício (2006).

The plots were (randomly) submitted to the following management models based on Bourgeois (1992): Plot 1 (P1) = Model for small diameters ($d < 25$ cm); Plot 2 (P2) = Model for medium diameters (25 cm $< d <$ 35 cm); Plot 3 (P3) = Control: without intervention; Plot 4 (P4) = Model for large diameters ($d \geq 40$ cm). Thinning operations were carried out on Plots P1, P2, and P4. The first thinning occurred at 7 years old. A second thinning, which also served as the final thinning for P1 and P2, took place at 11 years old. Additionally, a third thinning was exclusively applied to Plot P4 (large diameters) at 16 years old. The shoots selection was carried out according to the qualitative criteria of stems for timber and vigor in order to ensure well-formed stems for the final clear cut, and making available logs with commercial dimensions easily saleable. Detailed information about this trial can be found in Patrício et al. (2020).

Data for the high-forest system was collected from permanent research plots located in the region of Bragança, NE Portugal (Figure 1). These plots were established in 2002 in young stands, ranging from 3 to 7 years of age, on privately owned land (afforested abandoned agricultural lands). To ensure an adequate number of adult trees per hectare at the end of the prescribed management plan, a plot area of 3000 m2 was selected with the aim of primarily producing high-quality timber. The plots were inventory periodically in 2008, 2011 and 2019, providing a dataset that includes information on stand growth dynamics within the 3–24 years' age interval. The stands were not thinned during this period. The observed reduction in density was primarily attributed to plant failure in the early years of plantation. For further details, please see Patrício (2006).

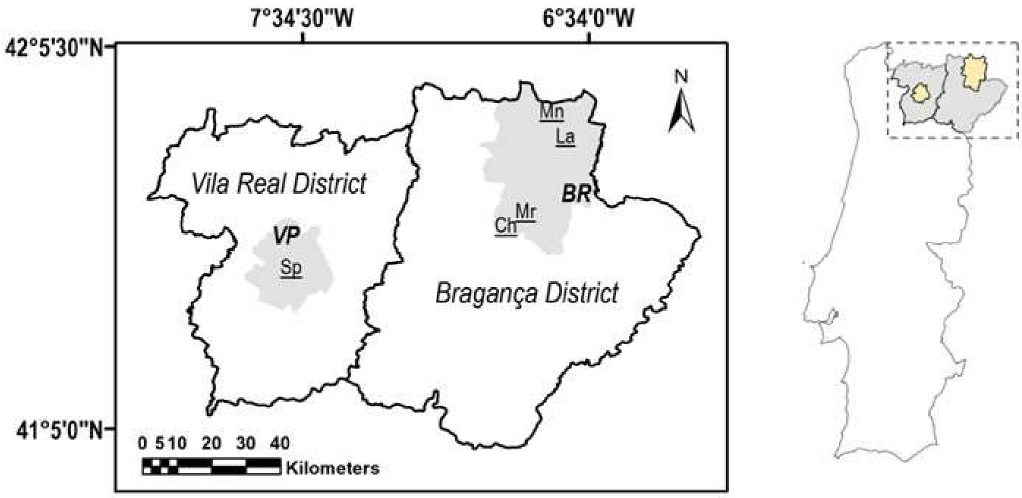

Figure 1. Location of the sweet chestnut stands. The young high-forest stands are located in Bragança (BR), specifically Montesinho (Mn), Laviados (La), Moredo (Mr) and Chãos (Ch). The coppice plots are in Serra da Padrela (Sp), Vila Pouca (VP).

Methods

To compare the growth and yield between the coppice and high-forest systems, in a first step we focused in selecting high-forest stands with a similar site index (SI) to that of the coppice stand. Since there was no specific SI equation available for Portugal, we utilized an equation developed for the northwest region of Spain by Menéndez-Miguélez et al. (2015, 2016) to estimate the SI for the coppice stands. Subsequently, by employing the SI equation developed by Patrício (2006), we identified adequate high-forest stands for the intended comparisons.

In a second step, we employed previously developed equations specific to each system to calculate stem volumes (m^3) within the plots. These volumes were then converted to a per-hectare basis ($m^3\ ha^{-1}$) based on the respective plot area. For the coppice system we used the equation developed by Patrício et al. (2020): $v = 0.0005318 + 0.00003773\ d^2h$, were v is individual-tree stem volume (m^3), d is stem diameter measured at 1.30 m from the ground (cm) and h is tree total height (m). Similarly, for the high-forest system the equation developed by Patrício (2006): v = 0.01516 + 0.0000324 d^2h, with the same variables and units as above.

In the third step, we obtained estimates of biomass, specifically stem biomass, by converting the volume measurements. To perform this conversion, we used the wood density value (ρ = 0.547 g cm^{-3}) as provided by Luís and Monteiro (1998). Furthermore, mean annual increment (MAI) and periodic current increment (CI) were computed for both cumulative stem biomass and stem volume per hectare.

RESULTS AND DISCUSSION

The estimated average site index for the coppice trial was 15 m of dominant height (hdom) at 20 years (SI_{20} = 15 m). Using this estimate, a high-forest stand located in Moredo, Bragança, which exhibited a similar SI and closely matched measurement dates to the coppice system, was selected for the purpose of comparing growth and yield. Dendrometric characteristics of the stands were summary separately for the coppice (Table 1) and the high-forest (Table 2).

Table 1. Summary of dendrometric variables up to age 24 in the plots of the coppice system.

Plot	Age	N_{st}	N_{sh}	hg	hdom	G	g_{sh}	dg	ddom	h/d	d_{mean}
P1	7	636	3473	7.0	7.9	11.6	0.003	6.5	11.3	111.8	6.2
P1	11	636	1501	9.6	11.2	12.6	0.008	10.3	14.9	98.6	10.1
P1	16	623	1450	12.5	13.4	20.5	0.014	13.4	18.3	93.0	13.1
P1	24	611	1399	13.0	15.4	30.4	0.022	16.6	23.2	80.7	16.2
P2	7	654	3778	7.5	9.1	13.6	0.004	6.8	11.9	117.1	6.4
P2	11	654	761	10.3	11.1	6.2	0.008	10.2	13.8	109.4	10.0
P2	16	654	761	12.7	13.7	13.5	0.018	15.0	19.8	86.3	14.7
P2	24	654	761	15.9	17.2	22.7	0.030	19.5	25.6	85.8	19.0
P3	7	618	6305	6.8	8.1	14.6	0.002	5.4	11.6	137.1	5.0
P3	11	618	5788	8.9	11.4	24.7	0.004	7.4	15.6	144.7	6.6
P3	16	593	3455	9.9	14.6	30.0	0.009	10.5	19.0	117.5	9.7
P3	24	454	1866	13.5	17.8	30.9	0.017	14.5	23.6	114.9	13.7
P4	7	574	2523	8.4	10.7	10.1	0.004	7.1	12.5	123.7	6.9
P4	11	531	534	10.3	11.7	4.3	0.008	10.1	13.3	110.8	10.0
P4	16	320	320	12.8	13.1	5.9	0.018	15.3	18.1	85.8	15.0
P4	24	320	320	16.7	16.9	10.8	0.034	20.8	24.3	81.0	20.0

Age of measumerent (years), N_{st} number of stools per hectare, N_{sh} number of shoots per hectare, ***hg*** height of the mean tree (m), ***hdom*** dominant height (m), ***G*** basal area of the stand (m^2 ha^{-1}), g_{sh} basal area of the mean tree (m^2 ha^{-1}), ***dg*** quadratic mean diameter or diameter of the mean tree (cm), ***ddom*** dominant diameter (cm), ***h/d*** mean stability coefficient, d_{mean} average diameter of the plot (cm).

Table 2. Summary of dendrometric variables up to age 24 in the high-forest stand with site quality similar to that of coppice.

Plot	Age	N	hg	hdom	G	g_{sh}	dg	ddom	h/d	d_{mean}
	7	933	5.7	6.5	3.8	0.006	7.5	11.1	83.3	7.0
HF[a)]	13	923	8.6	10.4	12.4	0.014	13.7	18.2	79.9	12.7
	15	907	10.6	11.6	15.1	0.017	15.2	19.5	81.1	13.9
	23	890	14.1	14.8	22.9	0.026	19.1	24.0	83.6	17.5

a) high-forest stand located in the region of Bragança, Portugal (denominated Moredo-B). ***N*** is number of trees per hectare; other variables and units are the same to that in footnote of Table 1.

Table 1 shows the evolution of stand variables over time in all the management models applied to the coppice system. It should be noted that management model prescribed in P4 (1 single shoot at the end of rotation) converges to a condition similar to that of the high-forest system. At age 24, the height of the mean tree (hg) and dominant height (hdom) are lower in the high-forest system compared to the coppice system, namely in the management model with similar target (P4). This trend is also observed when comparing with other coppice treatments. The coppice shoots developed using the root system carried over from a 50 years old high-forest, thus becoming full established. This vigorous height growth in the very early stages of the coppice is supported by the existing literature (e.g., Bourgeois et al., 2004; Alves et al., 2012).

From Tables 1 and 2, it is evident that the diameter of the mean tree (dg) and dominant diameter (ddom) show similarities between Plot 4 (P4) of the coppice system and the high-forest system up to age 24. However, there are some differentiation in *dg* (and d_{mean}) between the high-forest and both P1 (small diameters) and P3 (no intervention) in the coppice system, despite similar growth patterns observed in *ddom*. Furthermore, the stability coefficient (h/d) of trees in the management models applied in the coppice, approached that of the high-forest with the aging of the stand. This highlights the improvement in stem form resulting from sylvicultural management, leading to more resilient individuals against abiotic threats such as storms. Conversely, (P3) without intervention, presents thinner individuals with h/d coefficient values that remained above 100 up to age 24.

Tables 3 and 4 present the estimated stem volume (m^3 ha^{-1}) and stem biomass (t ha^{-1}) over time for the coppice and high-forest systems, respectively. In the coppice system, where thinning took place (P1, P2 and P4), the cumulative stem volume (V_cum) was calculated by summing the main stand volume (V_ms) at each measurement age with cumulative volume of thinning up to that age (Σ V_th), inclusively (Table 3). In P3, the same computations were performed, except that the values in the *V_th* column represent mortality events rather than thinning. In the high-forest, *V_cum* traduces the growth of the volume in the main stand (Table 4) as no thinning occurred and mortality was negligible.

Table 3. Stem volume and Biomass (yield and growth) in the coppice system up to age 24.

		Stem volume					Stem biomass		
Plot	**Age**	**V_th**	**V_ms**	**V_cum**	**MAI_v**	**CI_v**	**W_cum**	**MAI_w**	**CI_w**
P1	7	63.1	40.7	103.8	14.8	---	56.8	8.1	---
P1	11	45.6	60.8	169.5	15.4	16.4	92.7	8.4	9.0
P1 a)	16	2.9	121.5	233.1	14.6	12.7	127.5	8.0	7.0
P1 a)	24	3.3	194.3	309.2	12.9	9.5	169.1	7.0	5.2
P2	7	64.2	52.6	116.8	16.7	---	63.9	9.1	---
P2	11	94.2	32.9	191.3	17.4	18.6	104.6	9.5	10.2
P2	16	0	82.4	240.8	15.1	9.9	131.7	8.2	5.4
P2	24	0	178.8	337.2	14.1	12.1	184.4	7.7	6.6
P3 b)	7	27.0	53.3	80.3	11.5	---	43.9	6.3	---
P3 b)	11	1.3	123.7	152.0	13.8	17.9	83.1	7.6	9.8
P3 b)	16	21.0	176.4	225.7	14.1	14.7	123.5	7.7	8.1
P3 b)	24	27.5	243.3	320.1	13.3	11.8	175.1	7.3	6.5
P4	7	72.7	43.7	116.4	16.6	---	63.7	9.1	---
P4	11	68.6	23.2	164.5	15.0	12.0	90.0	8.2	6.6
P4	16	38.4	36.4	216.1	13.5	10.3	118.2	7.4	5.6
P4	24	0	84.9	264.6	11.0	6.1	144.7	6.0	3.3

Age of measurement (years), ***V_th*** volume from thinning (m^3 ha^{-1}), ***V_ms*** volume in the main stand (m^3 ha^{-1}), ***V_cum*** cumulative stem volume obtained in each measurement age as *V_ms* + Σ *V_th* (m^3 ha^{-1}), ***W_cum*** cumulative stem biomass (t ha^{-1}) calculated similarly to *V_cum*, ***MAI$_v$*** and ***MAI$_w$*** are mean annual increment in stem volume and stem biomass (m^3 ha^{-1} year^{-1} and t ha^{-1} year^{-1}, respectively), ***CI$_v$*** and ***CI$_w$*** are periodic current increment in stem volume and stem biomass (m^3 ha^{-1} year^{-1} and t ha^{-1} year^{-1}, respectively). a) V_th values in P1 at ages 16 and 24 refer to mortality, not thinning. b) volume reduction in P3 is only due to mortality.

Tables 3 and 4 show that, for comparable ages and site index, the coppice system consistently produces more stem volume than the high-forest system in all situations. As mentioned before, during the initial stages (up to 10 years of age), coppices in fertile sites can benefit from the root system of their parent trees, resulting in greater biomass production (and volume) compared to the high-forest system within the same time frame.

Table 4. Stem volume and Biomass (yield and growth) in the high-forest system up to age 24.

		Stem volume			Stem biomass		
Plot	Age	V_cum b)	MAI$_v$	IC$_v$	W_cum b)	MAI$_w$	IC$_w$
	7	22.2	3.2	---	12.1	1.7	---
HF a)	13	63.6	4.9	6.9	34.8	2.7	3.8
	15	81.7	5.4	9.1	44.7	3.0	5.0
	23	148.6	6.5	8.4	81.3	3.5	4.6

a) high-forest stand located in the region of Bragança, Portugal (denominated plot Moredo-B); b) ***V_cum*** (and ***W_cum***) refers to the natural growth of main stand as no thinning were applied (m^3 ha^{-1}); other variables and units are the same to that in footnote of Table 3.

The management model for large diameters (P4) in the coppice system produced more 100 m^3 ha^{-1} of stem volume at age 24, surpassing the high-forest (Figure 2A). However, the mean annual increment (MAI$_v$) in stem volume is still increasing in the high-forest system, while in the coppice it shows a declining trend (Figure 2B). In both Figure 2B and Table 3, it is evident that in coppice, the maximum values of MAI_v occurred around the age 11 in management models for small and medium diameters (P1 and P2), and even earlier (before age 7) in P4. These trends align with what has been reported by Bourgeois et al. (2004). In the unmanaged plot (P3), the maximum MAI_v was achieved later, after age 15.

In the coppice system, a mean annual increment in biomass (MAI$_w$) of 9 t ha^{-1} year^{-1} was achieved in P4, before reaching 10 year of age. At age 24, MAI_w in P4 decreases to of 6 t ha^{-1} year^{-1}. In the high-forest system MAI_w has been increasing approaching a value of 4 t ha^{-1} year^{-1} at age 24.

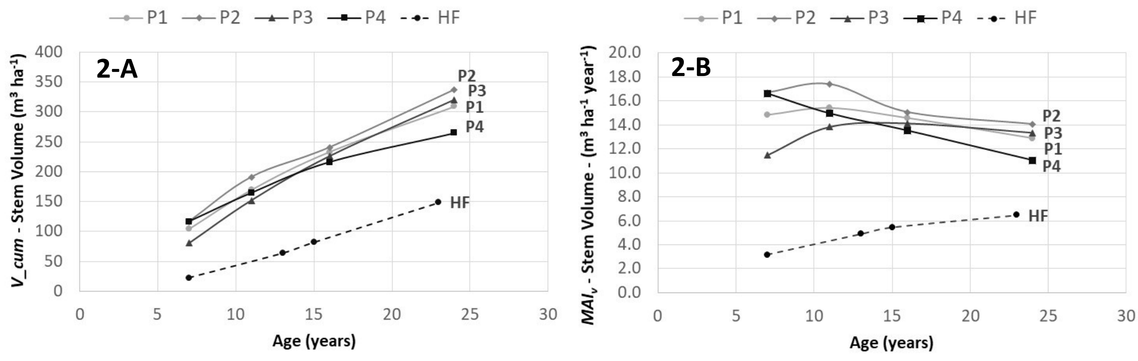

Figure 2. Cumulative stem volume in coppice (P1-P4) and high-forest (HF) up to 24 years of age (2-A); Mean annual increment of cumulative stem volume in coppice (P1-P4) and high-forest (HF) up to 24 years of age (2-B).

Regarding chestnut growth and production in high-forest and coppice systems in juvenile stage, the high-forest system generally exhibits lower height and diameter compared to the coppice system, particularly in the management model with similar targets. The vigorous height growth observed in the early stages of the coppice system can be attributed to the root system carried over from a 50-year-old high-forest.

The diameter of the mean tree and dominant diameter show similarities between the coppice system (P4) and the high-forest system up to age 24. However, there are differences in diameter between the high-forest and other coppice treatments. Sylvicultural management in the coppice system has led to improved stem form, indicated by the stability coefficient approaching that of the high-forest.

Relatively to stem volume and biomass coppice system, especially the management model for large diameters (P4), produces higher stem volume and biomass compared to the high-forest system in the juvenile stage. However, the mean annual increment in stem volume shows a declining trend in the coppice system, while it continues to increase in the high-forest system.

It is possible to extend rotations and apply suitable management models in the coppice system to improve its potential for sawlog production and obtain more valuable timber assortments. Innovative management alternatives in the coppice system can still lead to the production of considerable amounts of biomass from thinnings. However, this objective does not necessarily guarantee the production of better quality wood at medium/long rotations. For the production of high-quality wood, the high-forest system is more suitable since it exhibits continuous growth over a longer period, allowing for the development of larger dimensions.

Therefore, while the coppice system can be optimized for increased production and biomass utilization, the high-forest system remains preferable when the objective is specifically focused on producing high-quality wood.

CONCLUSIONS

It is known that high-forest stands of valuable broadleaves such as chestnut can produce high-quality timber in high fertility sites if proper sylvicultural management is applied. In this work, after comparing growth and yield of high-forest and coppice systems of similar (medium to high) site quality, we conclude that managing coppice for a final target similar to high-forest introduces flexibility in sylviculture. This approach enables allowing both high amount of biomass production in young stages, and long-lived products at the end of rotation.

By maintaining or even increasing the benefits derived from ecosystem services related to environment (including GHG emissions mitigation benefits), this flexible and tree-oriented sylviculture can improve the returns for landowners and contribute to the sustainability and development of the bioeconomy in mountain regions.

ACKNOWLEDGEMENTS

The authors are grateful to the Foundation for Science and Technology (FCT, Portugal) for financial support by national funds FCT/MCTES to CIMO (UIDB/00690/2020); AGRO Program, Project 267: Sustainable Management of Chestnut Forested Areas in High-Forest and Coppice Systems; Project PTDC/AGRCFL/68186/Mixed forests: Modeling, dynamics and geographical distribution of productivity and carbon storage in mixed forest ecosystems in Portugal; Project PDR2020-101-031671 GO_FTA: Afforestation of agricultural lands with+ value, financial support of FEADER and Portuguese Government.

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