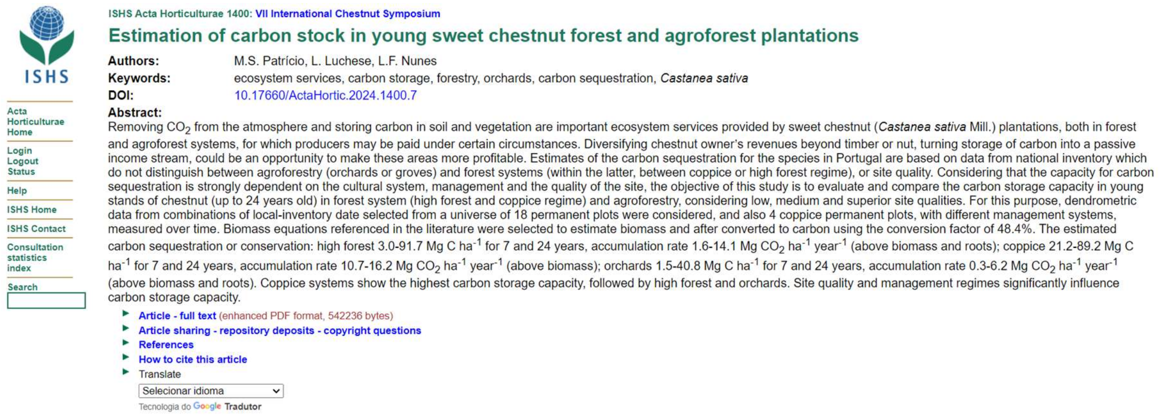

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Estimation of carbon stock in young sweet chestnut forest and agroforest plantations

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Keywords: ecosystem services, carbon storage, forestry, orchards, carbon sequestration, *Castanea sativa*
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Removing CO_2 from the atmosphere and storing carbon in soil and vegetation are important ecosystem services provided by sweet chestnut (*Castanea sativa* Mill.) plantations, both in forest and agroforest systems, for which producers may be paid under certain circumstances. Diversifying chestnut owner's revenues beyond timber or nut, turning storage of carbon into a passive income stream, could be an opportunity to make these areas more profitable. Estimates of the carbon sequestration for the species in Portugal are based on data from national inventory which do not distinguish between agroforestry (orchards or groves) and forest systems (within the latter, between coppice or high forest regime), or site quality. Considering that the capacity for carbon sequestration is strongly dependent on the cultural system, management and the quality of the site, the objective of this study is to evaluate and compare the carbon storage capacity in young stands of chestnut (up to 24 years old) in forest system (high forest and coppice regime) and agroforestry, considering low, medium and superior site qualities. For this purpose, dendrometric data from combinations of local-inventory date selected from a universe of 18 permanent plots were considered, and also 4 coppice permanent plots, with different management systems, measured over time. Biomass equations referenced in the literature were selected to estimate biomass and after converted to carbon using the conversion factor of 48.4%. The estimated carbon sequestration or conservation: high forest 3.0-91.7 Mg C ha^{-1} for 7 and 24 years, accumulation rate 1.6-14.1 Mg CO_2 ha^{-1} $year^{-1}$ (above biomass and roots); coppice 21.2-89.2 Mg C ha^{-1} for 7 and 24 years, accumulation rate 10.7-16.2 Mg CO_2 ha^{-1} $year^{-1}$ (above biomass); orchards 1.5-40.8 Mg C ha^{-1} for 7 and 24 years, accumulation rate 0.3-6.2 Mg CO_2 ha^{-1} $year^{-1}$ (above biomass and roots). Coppice systems show the highest carbon storage capacity, followed by high forest and orchards. Site quality and management regimes significantly influence carbon storage capacity.

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Estimation of carbon stock in young sweet chestnut forest and agroforest plantations

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Abstract

Removing CO_2 from the atmosphere and storing carbon in soil and vegetation are important ecosystem services provided by sweet chestnut (*Castanea sativa* Mill.) plantations, both in forest and agroforest systems, for which producers may be paid under certain circumstances. Diversifying chestnut owner's revenues beyond timber or nut, turning storage of carbon into a passive income stream, could be an opportunity to make these areas more profitable. Estimates of the carbon sequestration for the species in Portugal are based on data from national inventory which do not distinguish between agroforestry (orchards or groves) and forest systems (within the latter, between coppice or high forest regime), or site quality. Considering that the capacity for carbon sequestration is strongly dependent on the cultural system, management and the quality of the site, the objective of this study is to evaluate and compare the carbon storage capacity in young stands of chestnut (up to 24 years old) in forest system (high forest and coppice regime) and agroforestry, considering low, medium and superior site qualities. For this purpose, dendrometric data from combinations of local-inventory date selected from a universe of 18 permanent plots were considered, and also 4 coppice permanent plots, with different management systems, measured over time. Biomass equations referenced in the literature were selected to estimate biomass and after converted to carbon using the conversion factor of 48.4%. The estimated carbon sequestration or conservation: high forest 3.0 – 91.7 Mg C ha^{-1} for 7 and 24 years, accumulation rate 1.6-14.1 Mg CO_2 ha^{-1} $year^{-1}$ (above biomass and roots); coppice 21.2 – 89.2 Mg C ha^{-1} for 7 and 24 years, accumulation rate 10.7-16.2 Mg CO_2 ha^{-1} $year^{-1}$ (above biomass); orchards 1.5– 40.8 Mg C ha^{-1} for 7 and 24 years, accumulation rate 0.3-6.2 Mg CO_2 ha^{-1} $year^{-1}$ (above biomass and roots). Coppice systems show the highest carbon storage capacity, followed by high forest and orchards. Site quality and management regimes significantly influence carbon storage capacity.

Keywords: *ecosystem services, carbon storage, forestry, orchards, carbon sequestration, Castanea sativa*

INTRODUCTION

Forests play a vital role in mitigating climate change providing a crucial mechanism for sequestering and storing carbon. This valuable function of forest ecosystems is recognized as a regulating service according to the Millennium Ecosystem Assessment (MEA, 2005). During the growth process, trees and other forest plants remove substantial amounts of carbon dioxide (CO_2), a greenhouse gas (GHG), from the atmosphere, and store the carbon in their biomass through photosynthesis. This highlights the significance of this ecosystem service in maintaining global climate stability. The establishment of markets specifically for ecosystem services is considered essential for the preservation of the ecosystems providing these services (Deal et al., 2012).

According to UNEP (2008), payments for ecosystem services (PES) deals are emerging wherever businesses, public-sector agencies, and nonprofit organizations have taken an active interest in addressing particular environmental issues. These schemes provide a new source of income for land management, restoration, conservation, and sustainable use activities, and therefore have significant potential to promote sustainable ecosystem management.

The significant presence of sweet chestnut (*Castanea sativa* Mill.) across Europe, covering more than 2.5 million hectares of forested land, predominantly in Mediterranean and Sub-Mediterranean regions (Conedera et al., 2021), holds great significance in this context.

The valuation of ecosystem services considered as public goods, such as carbon, can be a key factor for the revitalization of many abandoned or poorly managed chestnut areas. Recognizing the significance of ecosystem services provided by forests and agroforests of sweet chestnut is vital for their preservation and enhancement.

PES schemes can provide payments to landowners who adopt sustainable management practices that improve carbon storage or integrate agroforestry practices that increase carbon sequestration, thereby offering additional economic benefits (Pagiola et al., 2005; Wunder, 2008; Kinzig, 2011). PES schemes have emerged in several regions and continents as a means of addressing various environmental concerns. In particular, carbon sequestration has been a focus of such programs, with notable examples found in China (Liu et al., 2008) and the United Kingdom (Dobbs and Pretty, 2004).

Emerging markets and the implementation of market-based payments for ecosystem services are gaining traction. Well-designed markets and market-based payments for ecosystem services can create economic incentives for private landowners to own and engage in sustainable management of forestland. As a result, they can be appropriately rewarded for their role in delivering essential and life-supporting services that benefit society as a whole (Heal, 2000; Collins et al., 2007). A combination of multiple mechanisms is often used to address the complex challenges associated with carbon capture and storage by forests, including subsidies, taxes, cap-and-trade schemes, voluntary carbon markets, sponsorship, certification, etc.

In this context, any initiative aimed at assigning value to carbon as an ecosystem service or C-credit inherently involves the process of carbon accounting and measurement. In Portugal, the sweet chestnut covers an area larger than 48,000 ha considering the National Forest Inventory (ICNF, 2015), including traditional orchards or groves, high-forest, and coppice woodlands (Patrício et al., 2022). It stores approximately 16.6 Gg CO_2e. However, this value does not differentiate the chestnut areas based on agroforestry or forest systems (including high forest or coppice), nor does it account for variations in quality class.

The absence of this information in the National Forest Inventory creates a gap, making it challenging to provide accurate estimates of biomass and carbon capture for different chestnut production systems. To address this gap, the objective of this study was to obtain reliable estimates of biomass and carbon capture specifically for chestnut in agroforestry and forest systems, taking into account quality classes. Additionally, the study aimed to distinguish between high forest and coppice cultivation within the forestry system, utilizing data collected from specifically permanent plots monitored over time. The estimates presented in this study focus on young chestnut stands up to 24 years old, as these are the age groups with the highest potential for carbon sequestration. Furthermore, the study intends to provide an estimation of the potential carbon valuation based on the selected replacement market, which is the EU Emissions Trading Schemes (EU ETS).

MATERIALS AND METHODS

Network plots

Regarding high forest stands, we have utilized data collected from research permanent plots that were installed in 2002 to monitor the growth and yield of the stands over time. These plots were situated in privately owned Sweet chestnut forest plantations, located on abandoned agricultural land. The dataset includes information from 15 plots, each covering

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an area of 3,000 m^2, established within very young chestnut stands ranging in age from 3 to 7 years. These plots were subsequently measured again in 2008, 2011, and 2019, providing additional longitudinal data for analysis from 3 to 23 years of age. The stands were not thinned during this period. The reduction of density observed was due to plant failure in the early years of plantation. General characteristics of these sites can be found in Patrício (2006).

Additionally, we have incorporated data from a research trial established in 1981, specifically designed to study the dynamics of Sweet chestnut and Douglas fir in various mixtures. For the purposes of our study, we have exclusively focused on pure chestnut plots. Detailed information regarding the aforementioned research trial can be found in Luís and Monteiro (1998).

The data collection was carried out within the Bragança region, encompassing the Municipalities of Bragança and Vila Flor, located in northeastern Portugal (Figure 1).

In each plot, and period of time, all trees were measured for the diameter at breast height d (1.3 m above ground) (if applicable), and total height h. A series of periodic evaluations were conducted, resulting in a total of 160 inventories being applied across the 18 high forest chestnut plots.

For the sweet chestnut coppice, data from a research trial conducted in Serra da Padrela (Figure 1), Municipality of Vila Pouca, in the northeast of Portugal, was utilized. The trial consisted of four permanent research plots, each covering an area of approximately 1000 m^2. These plots were established in 1994, within an even-aged coppice stand composed of 2-year-old shoots. The coppice stand was formed after the clear-cutting of a 50-year-old high-forest chestnut stand, which had a site index (SI_{45}) of 24m. The site index was estimated using the appropriate equation for high forest chestnut (Patrício, 2006; Patrício and Nunes, 2017).

The plots were subjected to different management models, based on Bourgeois (1992), and the allocation of these models was randomized as follows: Plot 1 (P1) received the model for small diameters (d < 25 cm), Plot 2 (P2) received the model for medium diameters (25 cm < d < 35 cm), Plot 3 (P3) served as the control with no intervention, and Plot 4 (P4) received the model for large diameters (d ≥ 40 cm). Thinning operations were carried out on Plots P1, P2, and P4. The first thinning occurred when the stands were 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) when the stand reached 16 years old. Detailed information about this trial can be found in Patrício et al. (2020).

Data from 24 years of coppice growth were utilized for analysis in this study.

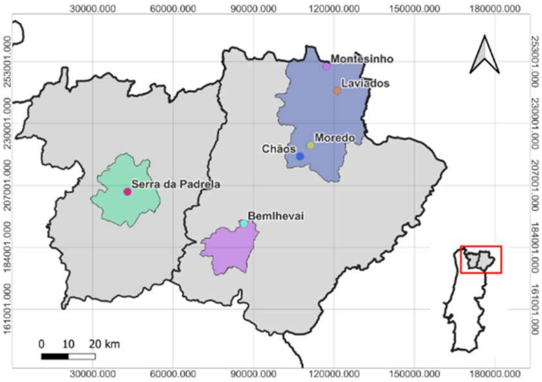

Figure 1. Location of the sweet chestnut stands

Data analysis

The high forest chestnut plots were selected and grouped based on their quality class. The site index (SI) for these plots was determined by using the dominant height and plantation age of the plots. The SI was calculated using the site index model developed by

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Álvarez-Álvarez et al. (2010), which is specifically constructed for young forest chestnut plantations (SI_{10}). The SI_{10} represents the estimated dominant height (in meters) of the plot at a reference age of 10 years. High forest chestnut plots were selected and grouped by quality class. The selection of the final plots was based on their suitability within site-specific index intervals, classified into three levels: upper (SI ranging from 10 to 12m), middle (SI ranging from 7 to 9m), and lower (SI ranging from 4 to 5m).

At the end, three plots were selected for the upper SI class, three plots for the medium SI class, and ten plots for the lower SI class. Each of these chosen plots corresponds to multiple inventories carried out at different time intervals. The dataset is characterized in Table 1.

Table 1: Characterization of the database corresponding to the high forest chestnut plots selected for this study.

Parameter	Mean	Minimum	Maximum	SD
Age (years)	12	3	23	5
N (trees ha^{-1})	1007	220	1357	210
d (cm)	8.1	0.3	28.3	4.7
h (m)	6.3	1.2	19.8	3.3
dg (cm)	8.9	1.5	19.1	4.0
hg (m)	8.3	3.0	15.7	3.0
ddom (cm)	12.2	2.3	24.0	5.2
hdom (m)	7.6	2.5	15.6	3.4
G (m² ha^{-1})	9.34	0.7	22.9	5.9
SI $_{(10)}$	7.3	3.6	12.5	2.3
Total Biomass (Mg ha^{-1})	34.0	0.17	183.6	42.1
Total Carbon (Mg ha^{-1})	16.5	0.08	88.9	20.4

N number of trees per hectare, **d** diameter breast height (1.30m above ground), **h** total height of the tree (m), ***dg*** quadratic mean diameter or diameter of the mean tree (cm), ***hg*** height of the mean tree (m), ***ddom*** dominant diameter (cm), ***hdom*** dominant height (m), ***G*** basal area of the stand (m^2 ha^{-1}), ***SI(10)*** site index for a reference age of 10 years old.

For chestnut forest (high forest), the biomass was calculated using the specific individual tree equation proposed by Patrício et al. (2005) and Patrício (2006), presented below:

$$W\_tot = 0.1236 * d^{2.3929}$$

The equation estimates the total dry biomass of the tree (W_tot) in kilograms (kg) based on the diameter with bark (d, in cm) measured at a height of 1.30 meters. The equation has an adjusted coefficient of determination (R^2Adj) value of 0.988, indicating a strong fit to the data. To determine the biomass of the root fraction in the high forest chestnut, the equations adjusted by Montero et al. (2005) were used.

The total biomass corresponds to the sum of individual biomasses (aerial and root) obtained from each plot. This biomass is then extrapolated to hectare and converted into metric tons per hectare (Mg ha^{-1}).

For the agroforestry system, the estimation of aerial biomass was calculated using the stand equation proposed by Menéndez-Miguélez et al. (2023). This equation is specifically constructed to estimate the aerial biomass in agroforestry systems. The equation takes into account the density, site index (SI), and age of the stand:

$$Wstand\_ha=(1787.40-147.60 * X_2) * T^{(-1.1235+ 0.0003 * X_1+0.2863 * X_2)}$$

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In this equation, Wstand_ha represents the biomass per hectare (Mg ha^{-1}), X_1 represents the density of the stand, X_2 represents the site index (SI), and T represents the age of the stand. The adjusted coefficient of determination is R^2Adj=0.931.

In traditional orchards (high forest grafted for nut production), the respective quality classes were defined based on SI values of 5m, 7m, and 11m.

The biomass in the agroforestry stands was calculated using two different densities corresponding to planting spacing of 10 x 10 m and 7 x 7 m.

To estimate root biomass per hectare (Wrs) in agroforestry, the following equation proposed by Menéndez-Miguélez et al. (2023) was employed:

Wrs_ha=3.1502*T^(-0.7437)

To quantify the total biomass (Mg ha^{-1}) of chestnut agroforestry areas, the sum of aerial and root biomass of the stand was considered, taking into account the site index (SI), density of plantation, and stand age.

For chestnut coppice, the aerial biomass of the plots was estimated based on the volume using the volume equation proposed by Patrício et al. (2020). The equation specifically developed for the stand is as follows:

v = 0.0005318 + 0.00003773 * d^2 * h

In this equation, v represents the individual volume of the shoots (m^3), d represents the diameter at 1.30 m height (cm), and h represents the height of the shoot (m). The model has an R^2Adj of 0.98.

The volume obtained was converted to biomass using a conversion factor of 0.547, which corresponds to the density of chestnut wood (Luís and Monteiro, 1998).

For estimating root biomass in the chestnut coppice, average values of coppice root biomass were utilized, as provided by Bourgeois et al. (2004). This estimation of root carbon stock relies on a fixed value and, therefore, was not considered in the calculation of carbon sequestration for coppice.

The biomass obtained for each study plot was converted to hectares (Mg ha^{-1}), resulting in the stand biomass for the different silviculture models implemented.

In all situations, the biomass was converted to carbon using a conversion factor of 0.484 (Montero et al., 2005). This factor was validated by the average laboratory values reported by Patrício (2006).

For the carbon calculated for the various chestnut production systems, trend lines were fitted based on age and site index (SI).

The carbon value obtained for the different chestnut production systems was converted into CO_2 by multiplying it by the factor 3.67, as referenced in the literature.

Finally, to quantify the carbon valuation, the replacement market method (Vale, 2014; Lopes and Cunha-e-Sá, 2014) was employed. The price of a substitute good for which there is a market was assigned, which in this case is the emission rights (EU ETS) established by the European Union. Scenarios were created based on the minimum, medium, and maximum prices per ton of CO_2 in the emission rights market, starting from 2021. These prices were sourced from the SendeCO2 company website (https://www.sendeco2.com), consulted on 06/05/2023.

RESULTS AND DISCUSSION

For the carbon calculated in high forest chestnut forests and agroforestry orchards, trend lines were fitted based on age and site index (SI) within their respective production systems (Figure 2).

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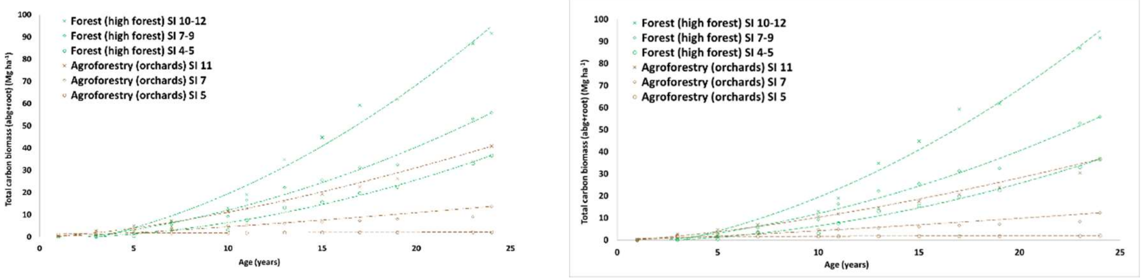

Figure 2: Total carbon (a) above ground and roots (abg+root) of the high forest chestnut and agroforestry (tree density 7x7m) classified into upper, middle, and lower quality classes. Total carbon (b) (abg+root) of the high forest chestnut and agroforestry (tree density 10x10m) classified into upper, middle, and lower quality classes.

As depicted in Figure 2, the upper quality class (SI_{10} 10-12) of chestnut High forest exhibits the highest total carbon stock, including both above and below-ground biomass. At the age of 24, the carbon storage reaches approximately 91.7 Mg ha^{-1}. For the quality classes middle (SI_{10} 7-9) and lower (SI_{10} 4-5), the stored carbon was approximately 55.9 Mg ha^{-1} and 36.7 Mg ha^{-1}, respectively.

Table 2: Guidelines for carbon storage/sequestration in biomass of different cultural systems of sweet chestnut considering site quality. Different management models were considered for coppice. Total biomass values (above and below ground) were calculated for high forest and agroforestry chestnut systems. Only aboveground biomass is reported for the coppice.

Cultural system	Approach	SI	Estimated biomass (Mg ha^{-1})*	Estimated C stored (Mg C ha^{-1})*	Estimated C sequestration (Mg CO_2 ha^{-1})*	Accumulation rate (Mg CO_2 ha^{-1} year^{-1})*
Forest	High Forest	Upper (SI_{10} 10-12)	19.6-189.4	9.5-91.7	34.7-336.3	5.0-14.1
		Middle (SI_{10} 7-9)	12.9-115.4	6.3-55.9	22.9-204.9	3.3-8.5
		Lower (SI_{10} 4-5)	6.2-75.8	3.0-36.7	10.9-134.6	1.6-5.6
	Coppice P1 *(small diameters)*	SI_{20}=15	56.8-169.1	27.5-81.9	100.8-300.4	14.4-12.5
	Coppice P2 (medium diameters)		63.9-184.4	30.9-89.2	113.5-327.6	16.2-13.6
	Coppice P3 (no intervention)		43.9-175.1	21.2-84.7	78.0-311.0	11.1-13.0
	Coppice P4 (large diameters)		63.7-144.7	30.8-70.1	113.1-257.1	16.1-10.7
Agroforestry	7x7 m	Upper (SI_{10} 11)	13.4-84.4	6.5-40.8	23.9-149.9	3.4-6.2
		Middle (SI_{10} 7)	6.0-28.3	2.9-13.7	10.6-50.3	1.5-2.0
		Lower (SI_{10} 5)	3.7-4.4	1.7-2.2	6.5-7.8	0.9-0.3
	10x10 m	Upper (SI_{10} 11)	12.7-75.8	6.1-36.7	22.5-134.8	3.2-5.6
		Middle (SI_{10} 7)	5.6-25.5	2.7-12.3	9.9-45.3	1.4-1.9
		Lower (SI_{10} 5)	3.2-4.3	1.5-2.1	5.6-7.7	0.8-0.3

*At 7 years old and for 24 years' old;

The total carbon stock (abg and root biomass) in high forest chestnut stands varies based on the quality class and age of the stands. The upper quality class (SI_{10} 10-12) exhibits the highest carbon stock, reaching approximately 91.7 Mg C ha^{-1} at the age of 24. The middle quality class (SI_{10} 7-9) and lower quality class (SI_{10} 4-5) have carbon stocks of approximately 56 Mg C ha^{-1} and 37 Mg C ha^{-1}, respectively. The trend lines (Figure 2) provide estimates for carbon stock at different ages within the respective quality classes of the high forest chestnut stands and agroforestry chestnut stands.

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The carbon stock in agroforestry orchards planted at a density of 10 x 10 m, for the same age, ranges from 2.1 to 36.7 Mg C ha^{-1}, depending on the quality class (upper, middle, or lower). For agroforestry orchards planted at a density of 7 x 7 m, the carbon stock ranges from 2.1 to 40.8 Mg C ha^{-1}.

Considering the carbon sequestration rates, which represents the accumulation rate of CO_2 in the biomass, they vary depending on the silviculture system and quality class. The highest sequestration rates are observed in high forest chestnut stands of the upper quality class (SI_{10} 10-12), approximately 14.1 Mg CO_2 ha^{-1} year^{-1} at 24 years old. Agroforestry orchards planted at a density of 10 x 10 m have sequestration rates of 5.6 Mg CO_2 ha^{-1} year^{-1} and Agroforestry orchards planted at a density of 7 x 7 m have sequestration rates of 6.2 Mg CO_2 ha^{-1} year^{-1} in the upper quality classes.

Coppice Forests: The carbon stock in chestnut coppice forests depends on the management model. Different interventions and management practices in coppice forests result in varying carbon stocks. The carbon stock ranges from 70.1 to 89.2 Mg C ha^{-1} at 24 years old. The carbon stock for small diameter classes (P1), was approximately 81.9 Mg C ha^{-1}, for medium diameter classes (P2) 89.2 Mg C ha^{-1}, for no intervention (P3) 84.7 Mg C ha^{-1}, and for large diameter classes (P4) 70.1 Mg C ha^{-1}.

Valuation: To quantify the carbon valuation, the replacement market method was employed, considering the prices per ton of CO_2 in the emission rights market.

We considered three valuation scenarios: the lowest price during the period 01/01/2021-06/05/2023, the average price and, the maximum price in the same period (Table 3).

Table 3: Scenarios for valuing CO_2 sequestration in sweet chestnut areas by production system and quality class at 24 years old. The valuation potential for CO_2 was carried out employing the replacement market method and considering three different scenarios: the lowest price during the period 01/01/2021-06/05/2023, the average price and, the maximum price in the same period.

Cultural system	**Approach**	**SI**	**Accumulation rate** (Mg CO2 ha^{-1} year^{-1})	**Minimum** valuation (33.43 €/Mg CO_2 Jan/21)	**Medium** valuation (70.49 €/Mg CO_2 Jan/21-May/23)	**Maximum** valuation (91.82 €/Mg CO_2 Feb/23)
Forest	High Forest	Upper (SI_{10} 10-12)	14.01	468.52	987.90	1286.84
		Middle (SI_{10} 7-9)	8.54	285.51	602.01	784.18
		Lower (SI_{10} 4-5)	5.61	187.51	395.38	515.02
	Coppice P1 *(small diameters)*	SI_{20}=15	12.52	418.47	882.38	1149.38
	Coppice P2 (medium diameters)		13.65	456.36	962.28	1253.47
	Coppice P3 (no intervention)		12.96	433.22	913.48	1189.90
	Coppice P4 (large diameters)		10.71	358.11	755.10	983.59
Agroforestry	7x7 m	Upper (SI_{10} 11)	6.25	208.88	440.43	573.71
		Middle (SI_{10} 7)	2.10	70.14	147.89	192.64
		Lower (SI_{10} 5)	0.33	10.99	23.18	30.19
	10x10 m	Upper (SI_{10} 11)	5.62	187.76	395.92	515.72
		Middle (SI_{10} 7)	1.89	63.08	133.01	173.26
		Lower (SI_{10} 5)	0.32	10.79	22.74	29.63

The prices used for the assessment were obtained from the EU carbon compliance market, specifically the Emissions Trading Schemes (EU ETS). Price information was obtained from the SendeCO2 website (https://www.sendeco2.com) accessed on 6/04/2023.

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The forest system, encompassing both high forest and coppice, demonstrates the highest financial outcomes in euros. The values obtained, even in the lowest scenario, are highly appealing, particularly within the best quality classes.

CONCLUSIONS

In conclusion, this study provides valuable insights into the carbon stock and sequestration potential of high forest chestnut stands, agroforestry orchards, and coppice forests. The findings highlight the significance of quality class, silviculture system, and management practices in determining carbon stocks and sequestration rates in chestnut production systems.

Recognizing the value of ecosystem services, including carbon sequestration, biodiversity conservation, and soil protection, which are regarded as public goods, is of utmost importance for the restoration of abandoned or poorly managed chestnut areas and the promotion of their sustainable management. Furthermore, in managed areas, there is an opportunity to implement sustainable practices that not only enhance carbon capture and storage but also generate substantial additional economic benefits that can vary across different scenarios (see Table 3 for potential scenarios).

In this regard, it is essential for chestnut land managers, landowners, or their organizations to acknowledge the potential of payment for ecosystem services (PES) and carbon credits. By adopting certified sustainable management practices, they can increase the value of their land by effectively demonstrating the positive impact of responsible forest management on ecosystem services, with a specific emphasis on carbon sequestration or storage.

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