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Production of Chestnut Coppice Biomass in a Framework of Low Mechanization and High Expectations to Combat Climate Change and Other Social Expectations

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Abstract: Climate change has become one of the most critical problems facing modern society. Sustainable forest management can be an important solution to counter the increasing concentration of carbon dioxide in the atmosphere. In particular, management of the chestnut forest could prove to be an effective strategy to absorb carbon dioxide as this species is characterized by sustained growth, so it has a high capacity to store carbon, and through the use of wood products, it is possible to sequester it for a considerable period. Chestnut (*Castanea sativa* Mill.) forests cover an area of about 800,000 ha in Italy, most of which is managed as coppice. It plays a central role in the Latium Region where its productive function is very important, as it provides timber of excellent quality. The purpose of this paper is to verify whether the current management of chestnut is efficient, as well as whether retractable wood products can contribute to the fight against climate change. The chestnut coppice located in the municipality of Tolfa (Lazio region, Italy) produces timber for 352 m^3/ha and stores about 390,000 kg of CO_2. Wood residues and losses during woodworking, together with emissions for the use of machineries, generate emissions of 368,000 kg of CO_2. The chestnut semi-finished products, with long-term use prospects, retain a net volume of 22,000 kg of CO_2. Although this is good for combating climate change, the amount of CO_2 stored is very low, less than 6% of the CO_2 stored by functional unit. Chestnut wood has a high versatility of use, so it could replace several products generated by fossil raw materials. Moreover, the implementation of precision forestry, the adoption of forest management more oriented to favor larger plants, the development of local economies and the reduction in the carbon footprint of the wood supply chain through the use of sustainable technologies would increase the capacity for climate change mitigation and increase the added value of its products.

Keywords: *Castanea sativa* Mill.; ecological footprint; carbon sink; climate change; climate-smart forestry

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1. Introduction

The growth of industrialization has significantly altered the global carbon cycle. The level of greenhouse gases in the atmosphere has increased considerably, with major effects on the weather–climate system. An increase of 1.0 °C (±0.2) compared to the pre-industrial level has been estimated [1,2]. The impact of this evolution on natural systems and humanity induces the adoption of effective mitigation and countermeasures [3].

The ecological footprint is one of the tools available to monitor human pressure on ecosystems. While on the one hand it records resource consumption, on the other hand, it recognizes the existence of the ecological surplus that expresses the amount of greenhouse gases absorbed [4–7]. Forest ecosystems, whose ability to absorb atmospheric

CO_2 contributes to combating climate change, are part of this framework. This is an ecosystem service widely recognized and documented in the scientific literature [8–10].

Forest ecosystems are recognized for their capacity to absorb CO_2 and fix it in woody tissues and soil. Referring to the role of plants, in the growth phase, there is the accumulation of CO_2 that remains in the wood for the complete life cycle, depending on the type of use [11–13]. In the successive phases of processing and use, however, there are energy-consuming processes that both physically and figuratively reduce the stored ecological surplus. The contribution to combating climate change is therefore a direct consequence of the following:

- Wood density, a parameter that depends on the species;
- Forest management approaches;
- Working processes in forests;
- Timber handling;
- Working processes in the sawmill.

It is known that tree growth responds to biological laws and requires appropriate climatic and soil conditions. In productive forests, thinning is the most effective strategy in terms of the trees' dimensional and structural characteristics to be felled during the final cut, with positive effects in terms of carbon sequestration [14]. Considering that the wood yielded from these trees is suitable for long-term use, timber is a meritorious commodity, even if the working processes to satisfy the standards for use generate emissions. Thus, there is great interest in developing an approach to account for the absorptions and emissions of CO_2 using the Life Cycle Assessment (LCA) methodology [15], recently updated [16]. The approach consists of evaluating all phases of the production cycle, starting from the CO_2 stored in the wood at the time of felling (functional unit), tracking all inputs and outputs related to the transformation process and their emissions, to arriving at final product associated with ecological surplus [17–19]. In this specific case, the objective is to determine the formal contribution of the net carbon dioxide surplus eligible for climate change mitigation purposes [20,21].

Many studies in this field have utilized LCA. Specifically, for chestnut, Martinez-Alonso and Berdasco [20] determined the carbon footprint of wood products from sweet chestnut (*Castanea sativa* Mill.) forests in northern Spain. Carbone et al. [21] assessed the net carbon dioxide surplus (Net-CDS) in coppiced chestnut forests in a volcanic area in central Italy.

The chestnut (*Castanea sativa* Mill.) is a tree species that is widespread in Europe and the Middle East (Figure 1). In Italy, it covers an area of approximately 770,000 ha [22,23], most of which are managed as coppices with standards [24]. This form of management is considered the oldest form of sustainable forest management in the Mediterranean area, focusing on rapidly producing woody biomass and environmental benefits [25–27]. The Lazio region is notable for having chestnut coppice forests with high average annual growth rates and high-quality physical–mechanical characteristics [28–32].

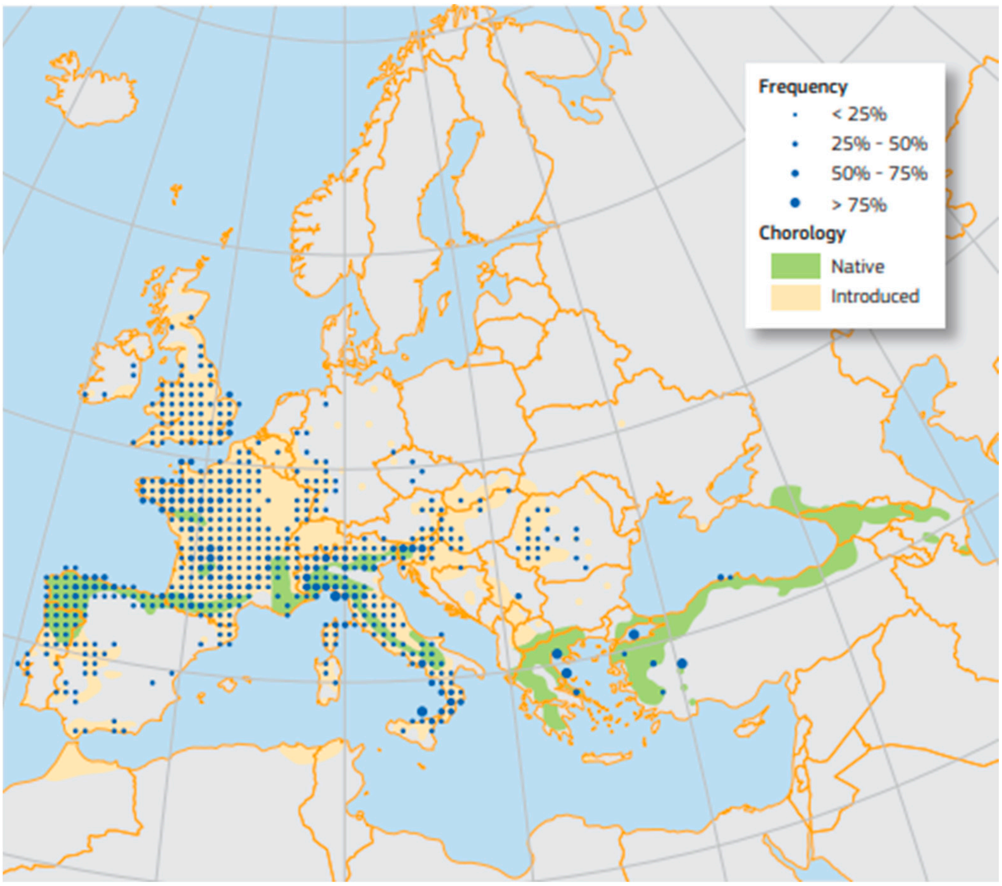


Figure 1. Geographical distribution of chestnut in Europe and the Middle East [33].

This study is part of a larger research project aimed at enhancing the tangible and intangible characteristics of chestnut coppice and chestnut wood. The hypothesis is to verify whether chestnut coppices can increase their performance both in woody production and in the provision of ecosystem services. In technical terms, this would mean a more efficient management of these semi-natural forest ecosystems, making a greater contribution both to combating climate change and to satisfying the community expectations (climate-smart forestry) [34].

It involves the first segments of the forest–wood chain, from forest management to sawmill. In order to implement forest management, forest farming involves the logging company. The use of tools, instruments, machines and machineries, both in the forest and in the sawmill, generates emissions that are offset by the CO_2 stored in the wood.

Using LCA with a multi-gate approach, the CO_2 balance was constructed, distinguishing the wood production destined for immediate use from that destined for long-term use. Only the latter part is effective for combating climate change.

2. Materials and Methods

2.1. The Study Area

2.1.1. Context

The study area is located within the territory owned by the local authorities of Tolfa that covers approximately 8000 ha, with a forested area of 2400 ha, mostly covered by coppiced stands of oak (*Quercus cerris* L.). It is included within the sites of the Natura 2000 network, identified as ZPS IT 6030005 Comprensorio Tolfetano Cerite Manziate, SIC IT 6030004 Valle di Rio Fiume, part of SIC IT 6030003 Boschi Mesofili di Allu- miere and part of SIC IT 6030001 Fiume Mignone (mid-course).

2.1.2. Tree Composition

The chestnut coppice area is situated to the northeast of the Lazio region (Figure 2) on the Tolfa mountains, in low relieves (400–800 m a.s.l.) of volcanic origin. The area covered by chestnut coppice is approximately 85 ha, which represents 4% of the entire forest property (2400 ha). In the area identified for the measurements, the predominant species is chestnut (83%), while the other species are present in small numbers (Figure 3).

Figure 2. Location of the chestnut coppice in the Tolfa area (Geoportale Regione Lazio, 2018) [35].

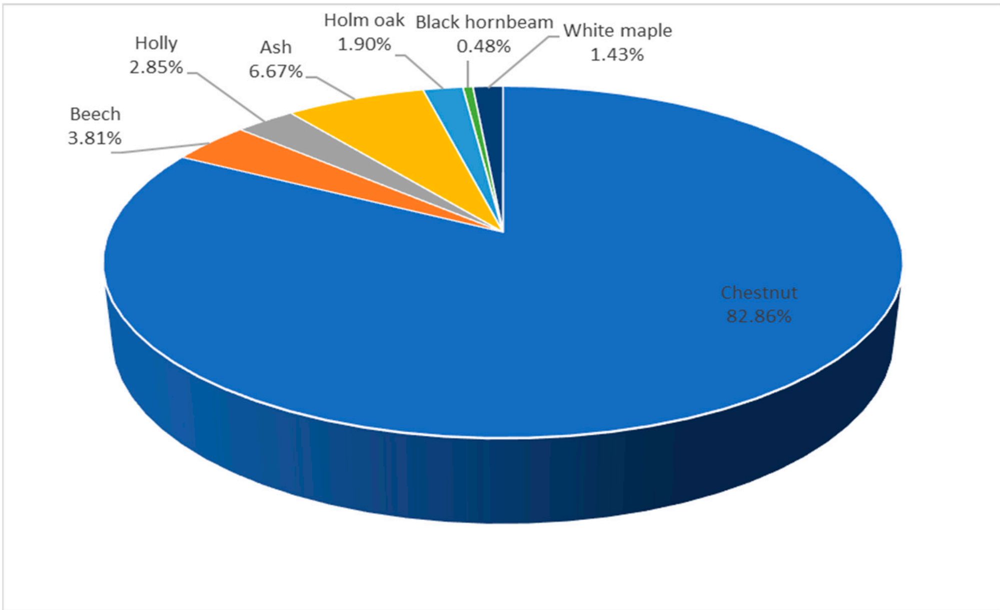


Figure 3. Tree composition.

2.1.3. Management

Traditionally, the management of chestnut wood was aimed at the production of fencing poles. The current Forest Management Plan, which will expire in 2028, adopted the conventional approach based on an essential silvicultural module. The plan suggests, eventually, a thinning between the age of 10 and 15 years, which in this rotation has not been implemented, while providing a final cutting at the age of 21 years and the release of 70 standards per hectare at the time of harvesting. After 21 years, the expected average of chestnut wood production is 164 m^3/ha. The prevision of the Forest Management Plan is very coherent to the data registered at the final cutting (Table 1).

Table 1. Main parameters of chestnut coppice according to the Forest Management Plan, implemented since 2013, and the current situation (2023).

Parameters	U of M	Expected Parameters in 2023	Parameters Registered in 2023
Age		28–31	28–31
Average diameter	cm	11.28	15.62
Average height	m	13.00	15.78
Average basal area	m^2/ha	25.38	26.83
Stand density	tree/ha	2815	2660
Expected average production	m^3/ha	164.00	169.23 [(1)]

[(1)] These data exclude the dead chestnut wood (150.35 m^3/ha) and wood from other species (33.22 m^3/ha). Including the 169.23 m^3/ha of chestnut wood for operational use, the total production of wood is 352.80 m^3/ha.

2.1.4. Forest Management and the Quantification of Standing Volume

The forest stand was subjected to final cutting during the 2022/2023 harvesting season. Prior to the work, an inspection was carried out to identify a plot that was representative of the entire forest in which to carry out the measurement operations. The circular plot has a radius of 10.38 m. All trees, except those left standing after the cut as standards, were sequentially numbered, and for each tree, the species and the diameter at breast height were recorded.

After felling and stacking of trees in a temporary storage area, the following measurements were taken for all chestnut plants:

- Total height;
- Height of stem until the diameter is 8 cm;
- Diameter of stem at 8 m in height.

It was considered useful to take these two additional measurements for the comparative volume analysis. For the other hardwood species (17%), the diameter and height parameters were measured using conventional methods.

2.2. Wood Productions and Use

The total volume of the sample plot was determined using the following method:

- For tree stems with prospects of long-term use, volume tables of the species “Chestnut”, under category “Volume stem and large branches (dm^3)”, was used [36];
- For dead trees, parts of trees, suppressed trees or other species, the diameter at 1.30 m was measured, heights were recorded with the Vertex instrument and the taper coefficient was acquired using the Forest Management Plan.

The total overall volume felled per unit area, the net of released plants, has been estimated at 352.80 m^3/ha (Figure 4), which represents the functional unit under study expressed in volume. The wood is distributed as follows:

- Chestnut wood for operational use covers 169.23 m^3/ha, of which 135.38 m^3/ha are destined for the sawmill, 20.31 m^3/ha for energy purposes and 13.54 m^3/ha released for natural decomposition;
- Dead chestnut wood, with a volume of 150.35 m^3/ha, has been allocated for energy purposes at 120.28 m^3/ha and 30.07 m^3/ha for natural decomposition;
- Wood from other species covers 33.22 m^3/ha, of which 23.25 m^3/ha is for energy purposes and 9.96 m^3/ha is released for natural decomposition.

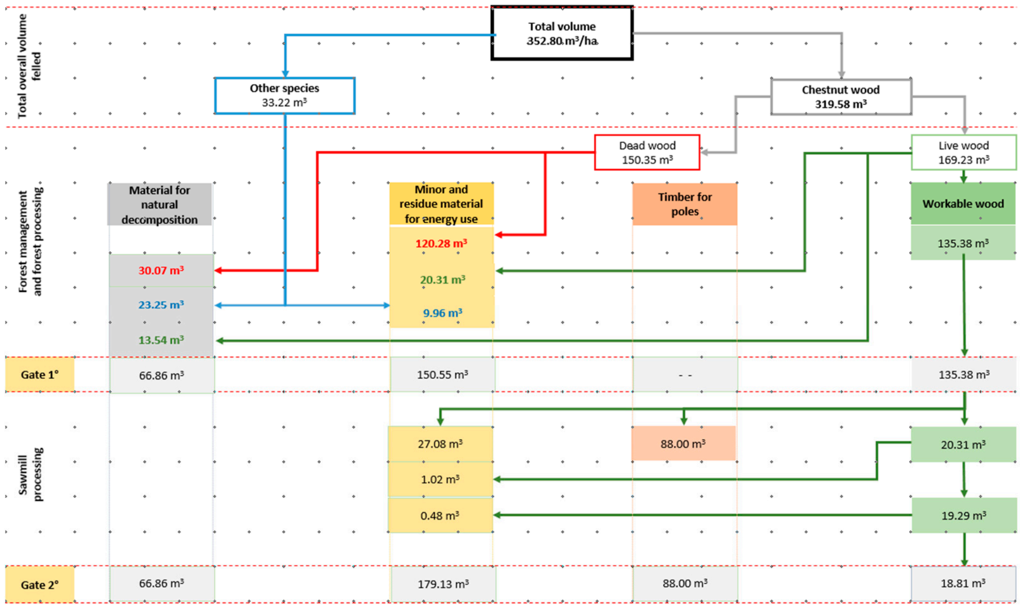


Figure 4. Reduction in the total overall volume and distribution of wood by category.

At gate 1, the destination categories are divided as follows: operational timber, 135.38 m^3/ha, which, following processing, has been allocated as follows:

- Workable wood, 20.31 m^3;
- Timber for poles, 88.00 m^3;
- Minor and residue material for energy use, 27.08 m^3.

The workable wood is first reduced to the required thickness and after drying for 3–4 years, undergoes final planning. At the end of this process, the volume introduced into the timber market (gate 2) amounts to 18.81 m^3. Given the initial volume, the allocation at gate 2 for the product categories is shown in Figure 5.

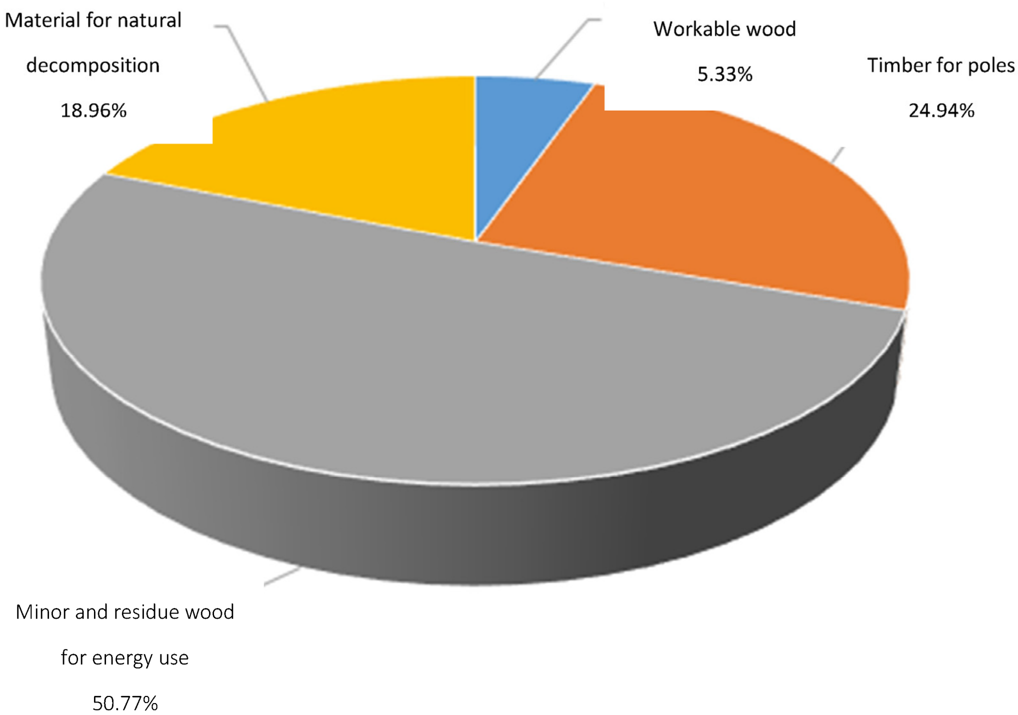


Figure 5. Distribution of the total overall volume by product category.

2.3. Wood Processing

The logging operation was carried out by a local forestry company that annually processes approximately 25,000 m^3/year of raw timber, mainly chestnut. The main equipment in the forest consists of chainsaws, a tractor with a winch and an excavator with a clamp. The felled trees were subsequently processed at the company's own sawmill, which is equipped with essential machinery, including a log saw and a band saw with a semi-automatic carriage and a thickness planer, in addition to other tools for material handling.

2.3.1. Forest Management

Forest felling was carried out by qualified workers using chainsaws. The felling operations involved chestnut and plants of other species, live, dead and/or dominated. After felling, branches were removed from the chestnut and other species. This waste material was released into the forest for natural decomposition. The timber of interest to the markets was extracted with a winch mounted on a tractor and was stacked in a temporary storage area. In chestnut trees, the plants are limbed, sectioned and the tops and damaged or curved parts are removed. The logs obtained were subsequently loaded onto the truck using an excavator with a clamp and then transported to the sawmill on a truck with a maximum capacity of 1.20 tons. The branches, curved tops and woody material from other species were loaded and taken to the company for appropriate processing, intended for their entry into the wood market for energy purposes.

2.3.2. Sawmill Processing

Upon arrival at the sawmill, the logs were unloaded in the temporary storage area. A qualified operator proceeded to qualify the individual logs on the basis of their dimensional characteristics and appearance, seeking the best possible end-use destination among the following categories:

- Workable wood: larger-sized logs, reduced to planks and subjected to natural seasoning. This material is stacked in special areas, and after 3–4 years of natural seasoning, it is processed using a band saw and thickness planer to obtain sharp-edged planks.
- Poles: a wide range of products that differ in diameter and height (Table 2) and are widely used outdoors. The name of the products are specific to the local area.
- Residual wood: this category includes wood residues obtained in the first selection in the forest (defective topping, etc.) as well as waste (defective wood, etc.) obtained from the processing of stems and branches in the sawmill, with a prospective allocation on the wood market for energy use.

Table 2. Range of products made of the chestnut coppice for category of timber for poles.

	Height m	**Diameter cm**
Min	1.50	5.00
Max	4.50	16.00

2.4. CO_2 Dynamics

2.4.1. Calculation of Absorptions

The following formula proposed from the IPCC [37] was adopted for the determination of CO_2 stored in wood:

$$\mathrm{V(CO_2)} = \left[\mathrm{ML} \times \mathrm{CC} \times \left(\frac{\mathrm{PA}_{(\mathrm{CO_2})}}{\mathrm{PA}_{(\mathrm{C})}}\right)\right] \quad (1)$$

where:

1. ML is the wood density;
2. CC is the carbon content in chestnut wood;
3. PA (CO_2) is the molar mass of CO_2;
4. PA (C) is the molar mass of C.

The specific weights of the different forest species present in the area are shown in Table 3. As regards chestnut wood, cross-sections were extracted from some of the felled plants in the plot area. The density was 607.11 kg/m^3, significantly higher than the conventional wood density for this tree species [38]. For the other species, the density was obtained from technical manuals, determining the average value given the specified value ranges for each species. Only for holly was it quantified as the average value among the companion species. The volume of CO_2 stored by the various species ranges from 1069.48 to 1564.74 kg CO_2/m^3.

Table 3. The specific weight of the different forest species.

Species	Density		CO_2 Absorbed
	Range of Density kg/m^3	Compute Density kg/m^3	CO_2 kg
Chestnut (1)	430–580	607.11 (1)	1069.48
Holm oak	710–1070	890	1564.74
Holly (2)	700–850	775	1362.55
Beech	680–970	825	1450.46
Ash	700–850	775	1362.55
Black hornbeam	620–820	720	1265.86
White maple	530–800	665	1169.16

Legend: (1) value determined by the Wood Technology Laboratory for Industry and Cultural Heritage, Department for the Innovation of Biological, Agro-food and Forestry Systems of the University of Tuscia, Viterbo. (2) Average value of accompanying species. Source: Peso Specifico Legno. Wiki-Fisica. Accessed on 11 October 2023.

2.4.2. Calculation of Emissions

The raw wood material is introduced into the forest–wood supply chain, undergoing processing first in the forest and then in the sawmill. These processes favor the re-emission of part of the stored CO_2 into the atmosphere, occurring through the following pathways:

- Indirect means, as a consequence of wood losses.
- Direct means, as a consequence of wood processing.

Indirect emissions are the result of processing raw wood, both in the forest and at the sawmill, to obtain assortments for long-term use. The overall resulting wood material (branches, curved tops, chips, sawdust, etc.) is generally classified as wood for energy purposes, thus destined for short-term to very short-term uses with the consequent re-emission of absorbed CO_2. In the case under study, the forestry company releases part of the residual material into the forest for natural decomposition. In both cases, the specific balance of the net emissions from processing is neutral.

Direct emissions are those released by fossil-fueled capital equipment which, in the Tolfa area, is traditional. These emissions are distinguished between the following:

(i) Actions: (a) forest management; (b) raw material management; (c) workable material management; (d) timber for pole management; (e) woody residue management; (f) monitoring, control and surveillance; (g) operation of the forestry company and sawmill.

(ii) Sources, which are distinguished between capital equipment such as (h) forestry equipment; (i) transportation equipment; (j) equipment for internal wood handling; (k) monitoring equipment, as well as other capital equipment, such as (l) permanently invested assets; (m) emissions generated for the production of instrumental assets.

For the purposes of calculation, the actions referred to in (a), (b), (c), (d) and (e), are as follows:

- Direct emissions, i.e., those generated by the use of instrumental assets for activities in the forest and at the sawmill. They are quantified as a product of the following variables:
    - ➢ Technical parameters [PT] (productivity, time of use, distances, etc.).
    - ➢ Energy [E].
    - ➢ CO_2 conversion coefficient [$CCCO_2$].
- Collateral emissions, meaning emissions generated by the monitoring, control and surveillance activities in the forest (letter f) (which depend on the kilometers travelled), as well as the energy used for administrative, accounting and commercial activities in the operation of the forestry company and sawmill (letter g) (quantified in terms of a percentage, equal to 0.8%).
- Remote emissions, i.e., emissions related to the CO_2 emitted when the structures were built where wood processing takes place (permanently invested assets), as well as when the tools used in the processes (instrumental assets) were produced, both by the forestry company and sawmill. For both types of assets, the quantification of emissions can be determined assuming that the emissions for the production of structural capital are known [CS], and these must be related to the years of their working life [Y] and the average annual volume worked [VML], obtaining the percentage of emissions per unit of worked volume [E(%)]. Formally, it is calculated by the following equation:

$$E(\%) = \frac{E(100\%)}{[Y] \times [VML]} \tag{2}$$

which in this case amounts to 16.71%.

Commonly, machines (chainsaw, truck, etc.) are powered by conventional fuel, while machinery is powered by electricity, which is made available from conventional power plants. The emission coefficients and specific unit emissions of machines and machinery are shown in Table 4.

Table 4. Specific unit emissions of CO_2.

	Action	Machines and Machinery	Power	Hourly Consumption [1] (Liters)	Distances (km)	Conversion Coefficient [2] CO_2 eq	Emissions CO_2 eq/Hour
Forest processing	Felling	Chainsaw	Fuel	1.25		2.66	3.3
	Sectioning	Chainsaw	Fuel	1.25		2.66	3.3
	Wood extraction	Tractor with winch	Fuel	5.62		2.66	14.9
	Loading logs	Excavator with clamp	Fuel	5.0		2.66	13.3
	Loading waste material	Excavator with clamp	Fuel	5.0		2.66	13.3
	Transportation	Truck	Fuel		52	2.66	
Sawmill processing	Unloading	Crane with hydraulic clamp	Fuel	5.0		2.66	13.3
	Internal handling	Crane with hydraulic clamp	Fuel	5.0		2.66	13.3
	Sectioning workable wood	Log saw	Electricity			0.55	
	Handling workable wood	Forklift	Fuel	5.0		2.66	13.3
	Stacking for seasoning of workable wood	Forklift	Fuel	5.0		2.66	13.3
	Handling seasoned workable wood	Forklift	Fuel	5.0		2.66	13.3
	Stacking workable wood	Forklift	Fuel	5.0		2.66	13.3
	Handling timber for poles	Forklift	Fuel	5.0		2.66	13.3
	Stacking timber for poles	Forklift	Fuel	5.0		2.66	13.3
	Handling residual wood	Crane with hydraulic clamp	Fuel	5.0		2.66	13.3
	Sectioning residual wood	Semi-automatic saw	Electricity			0.55	
	Stacking residual wood	Crane with hydraulic clamp	Fuel	5.0		2.66	13.3

Sources: (1) Data produced from experts; (2) UK Emissions Trading Scheme, Department for Environment, Food and Rural Affairs, UKETS (01)05rev2.

3. Results

3.1. Balance Sheet of CO_2

The construction of the balance sheet is based on the traditional framework that juxtaposes the assets with the liabilities, which in this case are the absorptions and emissions of greenhouse gases.

3.1.1. Balance Sheet—Active Section

The first item listed on the active side of the balance sheet is the functional unit, which is the initial endowment potentially available for climate change mitigation. It is represented by the amount of CO_2 absorbed by the coppice in the Tolfa area, predominantly chestnut, over 21 years of growth. The functional unit amounts to 389,746 kg CO_2/ha. Of this, 88% is attributed to chestnut wood, with approximately 41% unfortunately being dead standing wood due to the lack of thinning over time. Additionally, there is absorption from other species (12%) (Figure 6).

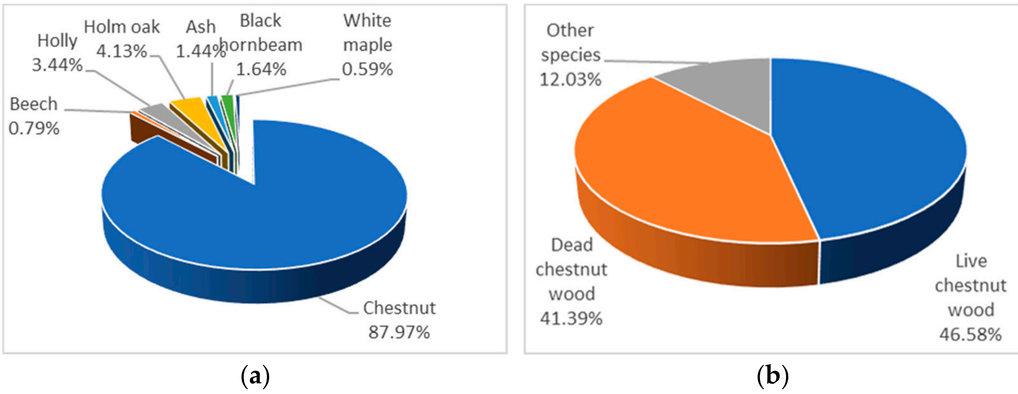


Figure 6. Contribution of forest species to the determination of the functional unit: (**a**) percentage contribution of each forest species; (**b**) percentage contribution of dead chestnut wood, live chestnut wood and other species.

3.1.2. Balance Sheet—Passive Section

The passive section, instead, is divided into two parts: (i) the loss of timber and (ii) the climate-changing emissions.

The Loss of Timber

In this section, the reduction in the useful timber volume along the processing chain is quantified in order to acquire the appropriate physical dimension characteristics for providing long-term services. The partial balance of the discarded timber, the net emissions due to the use of instrumental assets, is at a neutral balance because in the short term, the CO_2 stored during their growth is re-released into the atmosphere. In the context of climate change mitigation, the discarded volumes represent unaccountable losses. The objective of this section is therefore to estimate the fraction of CO_2 from the functional unit re-emitted into the atmosphere, both for the forest and sawmill processing.

The processing of felled raw timber in the forest is distinguished between that of live chestnut trees at the time of the operation, as well as other minor species, along with dead standing chestnut trees. Live chestnut trees, including shoots and standards, are reduced to transportable logs. This is achieved by removing the branches on the felling site and by trimming and eliminating the curved basal stubs. Other species and dead chestnut trees are processed on the felling site, removing the branches while also preserving the stems and branches (up to 5 cm in diameter) that can be sold on the energy market. In the sawmill, the chestnut logs are cut and directed to the following production lines: workable wood, timber for poles and timber for energy purposes. The quantification of woody volume losses is 333.99 m^3, while the quantification of losses in terms of CO_2 is 363,625 kg (Table 5).

Table 5. Analysis of losses by processing area and product category (data in kg of CO_2).

Gate		Description	Passive
	Forest	Branches	79,056
		Wood for energy use	163,997
1	Sub-total		243,053
	Sawmill	Timber for poles	93,928
		Wood for energy use (waste)	21,676
		Wood for energy use (trimmings)	4969
2	Sub-total		120,572
Total			363,625

Climate-Changing Emissions

The construction of the passive section involves the analysis of the actions and instrumental capital (sources) employed. Actions that generate direct emissions in the forest include the following

(a) Forest management, which is based on the felling of the stand, excluding standards to be left as part of the forest;
(b) Management of raw material, through the following:
    (b1) Clearing branches of all species, with the difference that for chestnut destined for construction timber, all branches are removed, while for other species and dead chestnut, stems and branches (hereafter referred to as FBR) of interest to the energy market are saved;
    (b2) Wood extraction is carried out using a tractor equipped with a winch, while for the FBR of other species and dead chestnut trees, they are first sectioned on the felling site and then harvested using a tractor with cages;
    (b3) Sectioning of only the logs at the storage area, with the removal of the curved basal stump and trimming to a length suitable for transportation;
(c) Loading of logs and FBR onto the truck;
(d) Transportation to the sawmill.

Upon arrival of the timber at the sawmill, the process continues with the following:

(e) Timber management, which involves the following:
    (e1) Unloading and allocating the timber to the two dedicated temporary storage areas for logs and other materials;
    (e2) From the temporary storage area, logs are moved to the processing area;
    (e3) Trimming and selection for the three production lines:
        (e3a) workable wood;
        (e3b) timber for poles;
        (e3c) timber for energy use.

The timber processing line (e3a) involves (i) trimming and thickness cutting; ii) formation of stacks; (iii) allocation of stacks in drying areas; (iv) after approximately 3–4 years, the timber is brought back to the processing area for thickness planning; (v) placement of semi-finished chestnut products on the market. The timber line for poles (e3b) involves (i) the sawing of poles to a defined length; (ii) formation of stacks by standard size classes; (iii) allocation of the poles to the market. Finally, in the timber processing line for energy use (e3c), waste and residual materials from forest operations are collected, excluding branches, while from sawmill processing waste, wood chips, sawdust, etc., are collected.

The other actions that generate collateral emissions include (a) monitoring and control, involving periodic inspections and minor maintenance interventions; (b) the operational activities of the company's administration and the sawmill.

Regarding emissions due to the use of instrumental capital, these include (a) forestry tools, especially the chainsaw, used for stand management, the processing of raw material, and the selection and trimming of logs; (b) machinery and equipment, such as the excavator with a hydraulic clamp for the loading and unloading of timber, the band saw, the thickness planer, as well as the machine for testing and controlling management activities; (c) transport and handling equipment, such as trucks and forklifts, the former for transporting timber from the management area to the sawmill, and the latter for internal handling of timber in various processing stages; (d) other instrumental capital (computers, printers, etc.) supporting administrative and commercial activities; (e) remote emissions resulting from the construction of structures for the storage of instrumental capital and the manufacturing of machinery and equipment used in the processing.

In Table 6, the emissions framework is constructed. Overall, the most emitting actions are those related to the management of raw material in the forest, 2716 kg of CO_2, while the management of timber along the production lines generates emissions of 1041 kg of CO_2. Forest management activities result in emissions of 234 kg of CO_2, and ancillary emissions are less than 100 kg of CO_2. The highest-emitting sources are machinery and equipment, accounting for 2243 kg of CO_2, with transportation and internal handling of timber within the sawmill estimated at around 1025 kg of CO_2. Remote emissions are slightly less than 600 kg of CO_2.

Table 6. Emissions generated by actions and sources (data in kg of CO_2).

			Actions					**Total Sources Emissions**
			Direct Emissions			**Collateral Emissions**		
			Forest Management	**Raw Material Management**	**Timber Management**	**Monitoring and Control**	**Operation**	
Sources	Direct emissions	Forestry tools	234.61				3.52	238.13
		Machines and machinery		874.06	395.03		33.15	1288.13
		Timber-handling vehicles		1453.66	496.89		15.14	1979.81
	Collateral emissions	Other instrumental capital				74.40	1.12	75.52
	Remote emissions	Capitals permanently invested and instrumental capital	39.18	388.73	148.95	12.42	8.84	598.12
Total action emissions			273.79	2716.45	1040.88	86.83	61.77	4179.71

3.2. Badget Balance of CO_2

The functional unit estimates an initial stock of 389,746 kg of CO_2/ha. Atmospheric emissions due to wood processing, between the forest and sawmill, are estimated at 363,625 kg of CO_2, while those due to the use of instrumental capital, whether direct, collateral, or remote, amount to approximately 4180 kg of CO_2. Therefore, the eligible balance for climate change mitigation purposes amounts to 21,940 kg of CO_2 (Table 7).

Table 7. Balance between active and passive (data in kg of CO_2).

Description	**Active**	**Passive**	**Balance**
Accumulated CO_2	389,745.51		
Emissions due to wood loss		363,625.54	
Emissions due to the use of instrumental capital		4179.71	
Balance	389,745.51	367,805.25	21,940.26

4. Discussion

In the pre-Apennine area of Lazio, areas of volcanic origin are the sites where chestnut trees for timber production find particularly favorable conditions for growth. The Tolfa territory is characterized by the presence of a small volcanic area, where there is a chestnut stand whose measurements show a production of approximately 353 m^3/ha at the age of 21 years, with an average increment of 16.8 m^3/ha, excluding standards released and including biomass. It is primarily a chestnut-dominated stand; however, a significant portion consists of standing dead chestnut trees because of the lack of thinning.

Unfortunately, this traditional approach to the management of chestnut coppices is recurrent in medium and medium–small farms, which are the most numerous but with smaller areas, less than 100 ha, in the Lazio region and also in large parts of Italy.

This is significantly reflected in the coppice's ability to optimize its CO_2 storage capacity. Although starting from a substantial CO_2 endowment, the eligible fraction is live chestnut (48%), while 43% is dead wood, plus 9% of wood of other minor species.

Following the forest operations (gate 1), 38% of the timber that enters the sawmill is classified as workable wood, while timber for energy use constitutes 43%. Finally, 19% is left in the forest for natural decomposition.

Since the chestnut trees are relatively small in size, of the 38% of the incoming volume at the sawmill, a significant portion goes into the production line for timber for poles (25%), while the remainder remains as workable timber (7%). This percentage is further reduced to 6% by the end of processing at the sawmill (gate 2).

The LCA reflects what was highlighted above in terms of CO_2 volume quantities. With an initial allocation of 389,746 kg of CO_2, the emissions resulting from the overall processing of timber amount to 363,625 kg of CO_2, which is 93% of the functional unit. In addition to these, there are the 4180 kg of CO_2 emissions due to the use of instrumental capital, which is approximately 1%. Therefore, the eligible fraction for climate change mitigation amounts to just 6%, approximately 21,940 kg of CO_2/ha. Extending the unit value to the entire forest area (85 ha) results in more than 2000 tons of CO_2.

The forestry management traditionally adopted, while providing a positive budget balance, could certainly do better. A substantial volume is destined for energetic uses due to an excess of plant density and the lack of intercalary maintenance. The implementation of the latter would increase the quantity and quality of timber for long-term use.

A comparative analysis of the environmental performance of chestnut coppices in the Tolfa area and those in the Colli Albani area [20] shows that the latter have better performance. Considering that the ($CO_2/m^{-3} \times ha^{-1}$) of usable wood volume in the compared forests is of the same entity, the differences arise from the high volume of timber discarded during the processing of the Tolfa coppices and the better silvicultural management practices in the Colli Albani forests, which include more intercalary management and a longer rotation period (Table 8).

Table 8. Chestnut coppice forests in comparison.

Chestnut Coppice	CO_2 of the Felled Volume in the Final Cut	CO_2 of Usable Volume	Environmental Performance Index	Rotation	Useful CO_2 Stored Annually	Useful Volume	CO_2 of Useful Volume
	CO_2/ha	CO_2/ha	%	anni	CO_2/anno	m^3	m^3/ha
Tolfa	387,766.38	16,106.81	4.15%	21.00	766.99	18.81	856.31
Colli Albani	547,875.00	107,444.00	19.61%	32.00	3357.63	125.00	859.55

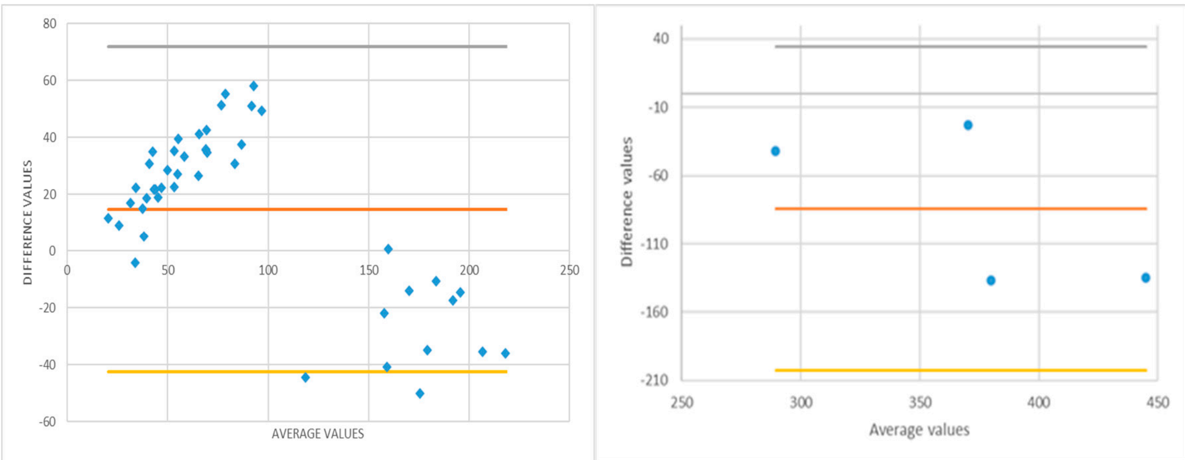
The current study's limitation lies in its company-scale focus, where the "specificities" of the context under investigation generate significant differences. The two parameters are focused on wood density and volume calculation. Nardi Berti [37] attributes a density of 430–580 Kg/m^3 to chestnut wood, while higher values have been recorded at the regional scale, specifically, 613 kg/m^3 for chestnut in the Colli Albani area and 607 kg/m^3 for chestnut in the Tolfa area. The data defined on a national scale would determine an underestimation ranging from 4.7% to 42.56%.

Regarding the amount of the growing stock, the value has been determined using national volume tables [36]. The values obtained refer to the average tree stem shape of chestnut shoots growing in Italian forests under various conditions. Comparing this method for estimating the volume of stems with the Smalian formula [39], which takes into account their actual shape, statistical parameters indicate that the average volume (shoots and standards) is slightly higher for the Smalian formula, while the standard deviation is greater for the volume tables (Table 9). In other words, according to the Smalian formula, individual stems have a smaller range of volumes. The volumetric data from both methods have also been compared using the Bland–Altman plot (Figure 7). There is a clear and statistically significant agreement between the two methods, as long as shoots and standards are kept separate in the analysis.

Table 9. Comparison of the methods adopted.

	Formula of Smalian	Volume Tables	Differences
Average value	0.115	0.108	6.10%
Standard deviation	0.081	0.115	−29.83%

In terms of volume per unit of surface area, the volume tables estimate 352.80 m^3/ha, while the Smalian formula records a volume of 363.13 m^3/ha, which is 2.93% higher. The differences between the two methods are not particularly significant; however, since this study was conducted at a company scale (microeconomic size), it is appropriate to consider the specific characteristics of the context. Although the variations from this study unit are limited, in terms of absolute values, they could be important. From the perspective of placing on the voluntary carbon credits market, underestimations could lead to significant economic and financial differences.



(**a**) (**b**)

Figure 7. Comparative analysis of samples using the Bland-Altman Plot. (**a**) Analysis of shoots; (**b**) Analysis of standards. (Limits calculation: upper limit (grey line, [average value +(2 × 1.96)]); average value (red line); lower limit (orange line, [average value −(2 × 1.96)]).

5. Conclusions

European Union policies for sustainable development converge toward the valorization of forest resources. Chestnut wood possesses qualities that make it suitable for structural uses and capable of providing long-term services. This versatility has generated significant interest in this species. Due to its multi-functionality, chestnut wood could be a competitive substitute for similar fossil-based raw materials [40].

The current study investigated the case of a coppice forest managed with an essential silvicultural model. Although the calculations showed a positive result, it must be emphasized that a large part of the production at the end of rotation, unfortunately, is not eligible for climate change mitigation purposes. Much of the wood production is destined for short to very short-term uses, resulting in a “zero-net” value balance. The emissions generated by the processing are offset by the preserved stock; however, there is potential to improve the environmental efficiency of these formations so they meet the criteria of the climate-smart forestry approach. Some suggestion are as follows:

- To exceed the current silvicultural model by incorporating thinning during a longer rotation period (up to 30 years) [14];
- To rationalize the current single-compartment layout to introduce a rotational system that allows for scalable management with reduced operational costs;
- To examine whether conditions exist to promote the extension of the rotation period;
- To upgrade the technology level of tools, machines and machineries used in the forest management and in the sawmill.

In terms of forest management practices, it is reiterated to move beyond conventional energy systems and promote the use of biofuels and renewable energy sources. In this regard, the next programming period could provide the necessary resources.

An aspect that deserves attention concerns chestnut pole production. Beyond the standardization of assortment categories [41] it is considered appropriate to develop a methodology for evaluating stored CO_2 so that these productions can also make a contribution to environmental issues.

From a methodological standpoint, the development of this study has highlighted some significant critical issues:

- LCA implementation requires detailed data. Unfortunately, their acquisition is difficult first of all, because operators are generally reluctant to provide data, as well as because Forestry logging companies often also carry out non-forestry activities, so it becomes difficult to obtain data specifically for forestry activities;
- National reference parameters are important for large-scale assessments, but on a micro-scale (forest farm), specific data for the studied context should be used, especially when there are economic objectives involved.

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