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Net-Carbon Dioxide Surplus as an Environmental Indicator for Supporting Timber Markets: A Case Study in Italy

Francesco Carbone [1,*], Piermaria Corona [2], Majid Hussain [3] and Francesco Barbarese [1]

[1] Department for Innovation in Biological, Agro-Food and Forest Systems (DIBAF), University of Tuscia, 01100 Viterbo, Italy
[2] Council for Agricultural Research and Economics (CREA), Research Centre for Forestry and Wood (CREA-FL), 00166 Rome, Italy
[3] Department of Forestry and Wildlife Management, University of Haripur, Haripur 22620, Pakistan
* Correspondence: fcarbone@unitus.it; Tel.: +39-0761-357748

Abstract: Using the Life Cycle Assessment (LCA) approach, environmental benefits in terms of CO_2 stored in chestnut wood in Italy have been calculated. Using one of the methodologies proposed under the LCA umbrella, a physical and formal balance sheet of CO_2 has been built. Chestnut forests (*Castanea sativa* Mill.) are one of the most critical forest types in Europe. They cover an area of 800,000 hectares in Italy, most of which are managed as coppices. Chestnut wood's high-quality physical-chemical and mechanical characteristics and medium-long durability explains its widespread uses. In this case study a section of a public forest in Central Italy (Lazio Region) has been considered. In the section, during the rotation, two types of intervention were carried out: thinning at 19 years of age, and final cutting at the age of 32. A production of 416 and 93 m^3ha^{-1} for final cutting and thinning, respectively, was recorded. The global amount of 507 m^3 is the functional unit, which has stored 547,875 $kgCO_2$. The combination of forest management and sawmill processing produces semi-finished chestnut timber products for 125 m^3, which have a physical storage of 135,210 $kgCO_2$. Using the formal balance sheet of CO_2, total emissions from processing were recorded for a total of 27,766 $kgCO_2$. At the exit of sawmill, products stored 107,444 $kgCO_2$, which is the amount of Net-Carbon Dioxide Surplus (Net-CDS). Transportation from sawmill to market reduces the sequestered CO_2 by 0.77 $kgCO_2$/km. The Net-CDS represents a competitive advantage in the timber market. If tree species have the same physical, chemical, mechanical and price parameters, the timber consumer would prefer to buy wood with the highest Net-CDS.

Keywords: *Castanea sativa*; chestnut timber; life cycle assessment; offset balance sheet of wood carbon dioxide; physical balance sheet of wood carbon dioxide; timber market

Citation: Carbone, F.; Corona, P.; Hussain, M.; Barbarese, F. Net-Carbon Dioxide Surplus as an Environmental Indicator for Supporting Timber Markets: A Case Study in Italy. *Forests* **2023**, *14*, 419. https://doi.org/10.3390/f14020419

Academic Editor: Barbara Ozarska

Received: 27 December 2022
Revised: 26 January 2023
Accepted: 14 February 2023
Published: 17 February 2023

1. Introduction

The signing of the United Nations Framework Convention on Climate Change [1] and the following Kyoto Protocol [2] created great expectations for the forestry sector. Forests represent the most significant green infrastructure worldwide and have been recognized as a carbon dioxide sink [3–7], and as such, protection and enhancement are the responsibility of society as a whole [8].

Clean Development Mechanisms refer to forest ecosystem services to increase the sequestration of CO_2. Such a function has been considered feasible for carbon accounting [9,10]. The ecological footprint is the most widely shared tool on a global scale to analyze development sustainability [11], and it has been primarily used on international, regional and national scales [12], as well as on a local scale [13,14]. However, there are few studies about the use of the ecological footprint as a marketing tool [15–17], even if this indicator can play a significant role in supporting the consumer in choosing environmentally friendly products. The ecological footprint includes the ecological surplus that expresses the volume of greenhouse gas (GHG) emissions sequestered by processes or goods. Wood is an ecosystem service that can store GHG emissions. In order to market timber products, forests must be managed, timber processed, and the timber products placed on the market. At the end of this process, the ecological surplus of wood is reduced due to the physical transformation of the raw material and transport (physical emission of CO_2), and CO_2 emissions in the working processes (formal emission of CO_2).

Conifers are the conventional wood reference [18] covering the largest global timber market demand, with a sizeable import-export flow. Locally, however, woody products are very difficult to establish on the market, despite their substantial physical and mechanical performance for structural employment. In a global context that pushes towards the use of low-carbon materials and from the perspective of enhancing local wood productions, the introduction of an indicator that highlights whether local wood production would contribute effectively to combating climate change, compared to timber imported from other areas, is desirable.

The case of the chestnut forest (*Castanea sativa* Mill.) is representative to this end. This forest tree species is widespread over all Europe, and in Italy, covers an area of approximately 800,000 hectares, largely managed by the coppice system [19]. Over 35,000 hectares are in the territory of the Lazio Region, of which around 80% are managed as coppices. The production of chestnut timber in Lazio has been distinguished by high yield in terms of workable wood [20,21]. Significant investments have been made recently to qualify chestnut timber in the structural sector and for other high value-added uses [20]. An indicator that highlights its environmental performance, that can be oriented towards the wood consumer, would be a significant innovation for the sector.

Life Cycle Assessment (LCA) [22,23] is a methodological tool, relevant in the sustainable green transition strategy [24] for quantifying the environmental performance of products or services according to the ISO 14040 standard. LCA results can also be used to support decision-making about production and consumption [25]. Gonzalez-García et al. [26] estimated GHG emissions for Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) plantations in Germany. The same approach has been used in Portugal by Dias and Arroja [27] by LCA of eucalyptus (*Eucalyptus globulus* Labill.) and maritime pine (*Pinus pinaster* Ait.) plantation management. Various management and mechanization systems have been analyzed to estimate the emissions gradient for the case under investigation. For example, Michelsen et al. [28] used a hybrid LCA methodology to assess the environmental impact and added value of *Picea abies* forestry operations in Norway, from seedling production to plant delivery onto the market. Martinez-Alonso & Berdasco [29] developed a chestnut wood case study: they investigated two scenarios regarding the use of kilns for reducing timber humidity to commercial standards, with both scenarios starting from the management of the forest and covering the whole chain until the allocation of semi-finished chestnut timber (SFCT) in the market.

In this paper, the functional unit is the total volume generated by a chestnut forest over an area of one hectare. The raw material is mainly processed to produce woody goods with a long life cycle in order to conserve the CO_2 stored in tissues. The whole forest-product chain of chestnut wood, from felling to the marketing of SFCT products, is considered. The CO_2 absorbed by chestnut trees during growth becomes the CO_2 stored in the wood. The CO_2 stored and emitted along the forest-market supply chain is estimated. The physical balance sheet of carbon dioxide and the offset balance sheet of carbon dioxide are provided. The net carbon dioxide surplus (Net-CDS) has been quantified from the offset balance sheet: it is a value of the gain of CO_2 stored in the wood with respect to that emitted along the whole forest-market supply chain. Knowing the Net-CDS implies having a parameter that allows you to quantify the capabilities of chestnut wood in the fight against climate change, it can also be used as an indicator to guide the responsible consumer in making purchasing decisions in the timber market. The conclusions also discuss green strategies that could further increase the absorption capacity of CO_2 in chestnut wood in order to make it even more competitive in the timber market.

2. Materials and Methods

2.1. Production and Processing of Chestnut Wood

2.1.1. Timber Production

The forest area under study is located south-east of Rome, within the Colli Albani landscape. It is a very fertile, volcanic area, where chestnut production can reach over 10 m^3 ha^{-1} $year^{-1}$, with rotation length between 20 and 40 years [30]. In this district, chestnut wood is characterized by a density of 613 kg m^{-3}, significantly higher than the conventional wood density for this tree species.

The forest section under analysis covers an area of 22.50 hectares and is managed according to a rotation of 32 years, with a thinning at the age of 19 years (Table 1).

Table 1. Forest section management data.

		Age	Shoots		Standard		Total Volume
		Year	**n/ha**	**m^3/ha**	**n/ha**	**m^3/ha**	**m^3/ha**
Thinning management	Before	19	2891	307	45	53	360
	After		1330	215	45	53	268
	Felled			92			92
Final cut	Before	32	1330	359	45	76	435
	After		45	20	-	-	20
	Felled		1285	339		76	415

2.1.2. Timber Process

Forest activities are carried out during the autumn-winter period according to regional forestry regulations. Activities are forbidden when weather conditions (snow, heavy rain) may cause soil damage and create hazardous work conditions. Stems are felled by qualified workers using chainsaws. Logging is undertaken using a winch mounted on a farm tractor. Felled stems (shoots and standards) are collected in a temporary storage area. Using a chainsaw, the plants are limbed, sectioned, and the tops and damaged or curved parts are removed, to obtain workable raw material (workable and secondary wood materials). All logs are loaded onto the lorry using the hydraulic clamp supplied with the lorry itself, while residual woody material (branches, twigs, top, curvilinear and other damaged parts) are reduced to chips by a wood chipper. A two-axle lorry is used to transport poles and chips to the sawmill.

Sawmills are located within a distance of about 20 km. When the lorries arrive, the logs are unloaded mechanically in the internal temporary storage area. Later, the logs are loaded onto the miter saw platform using a crane with a hydraulic clamp. According to the characteristics of the log, the operator identifies the most appropriate program in order to obtain the best wood assortments. The various logs are allocated to the dedicated temporary storage box. Log handling is carried out by crane, while forklifts are used for the shorter material. Logs are processed in the sawmill in order to obtain, first, timber products with high added value, such as beams, boards (workable wood material) and, to a lesser extent, other products, such as joists, or other sharp-edged timber products (secondary wood material). Using a crane with a hydraulic clamp, beams and boards are taken to the platform, which automatically loads the carriage. At the same time, the wood residuals are transported into the dedicated storage area.

The final step is drying beams and boards to 13% $\pm$ 2% water content of wood. There are two options: (a) natural drying, by piling up wood products outdoors for about four years; (b) artificial drying in kilns powered by electricity for a period of 45 days.

At the end of drying, the SFCT products are transported to the loading area by forklift and loaded onto three-axle articulated lorries with trailers. Once the lorry reaches its destination, it is unloaded by forklift. At the end of the unloading operation, it is assumed that the articulated lorry returns to its starting point.

2.1.3. Timber Products

The main categories of timber products obtained from raw chestnut wood are the following.

- Workable wood material (WWM): logs processed in the sawmill to obtain timber products with a long lifetime, obtained mainly from the final cutting. They are derived from the largest logs which are cut as long as possible, according to the maximum length that the lorry can accommodate (10–15 m); SFCT products are allocated into the dedicated markets.
- Secondary wood material: poles obtained mainly from thinning and final cutting (tree stems with breast height diameter less than 10 cm). These wood products are used in the agricultural sector to construct fences or other outdoor uses.
- Residual woody material: forest harvesting and sawmill residuals. The former refers to branches, damaged wood and other residual timber material, while residuals from sawmills include discards, scraps, shavings, sawdust, blocks, and other non-usable woody material. A large part of this material is chipped for energy use; this material is allocated into the biomass markets.

According to the short lifetime characterizing the last two categories, they are rearranged into minor wood material (MWM) categories.

2.2. Life Cycle Assessment

The UNI EN ISO 14040:2021 standard recently updated LCA. It provides a methodology by which the environmental impact of processes or products can be quantified, referring to their life cycle and assessing the energy consumption necessary for production, working process, use and disposal [22,23]. The first approach is “Cradle to Grave”, which involves the product’s entire life cycle. However, LCA has become an umbrella term in which new approaches have been included. Literature reports the approach “from cradle to cradle”, related to recycling products [31,32]; “from cradle to gate”, where the life cycle lasts until the exit of industry or market [33–35]; and “from gate to gate”, when the life cycle of products is considered from gate “i” to gate “i + 1” [36,37].

This study was characterized by the following elements:

- a combination of LCA approaches “cradle to gate” and “gate to gate”, achieving a novel “cradle to multiple gate” approach. The result of the environmental performance recorded at gate “i” was the input for the calculation of environmental performance at gate “i + 1”; given the environmental performance recorded in the transformation process, from “i” to “i + 1”; the gates in this study numbered four.
- the volume of chestnut wood between the beginning and the end of the rotation (t = 32 years) was the total production.
- the environmental performance included the annual management activities carried out in the forest section.
- compared to the conventional approach based on 1 m^3 as a functional unit, in this study the functional unit was the total production of chestnut during the rotation. Secondary and residual wood production were included in the assessment of environmental performance in terms of volume produced and emissions due to harvesting, and the corresponding CO_2 absorbed and emitted was registered.

The elaboration was developed using an analytical approach, taking into account the emissions due to:

- harvesting, processing and transportation activities from forest to market;
- the chipping of residuals from forest harvesting and sawmill;
- the annual activities of forest management along the rotation (e.g., checking and control);

- the administrative activities of the forest owner, the logging company and the sawmill; and
- the production of harvesting and sawmill machines and other tools, used in the forest and sawmill, as well as the construction of buildings and other infrastructure.

2.3. LCA of Chestnut Timber Products

2.3.1. Functional Unit

The chestnut wood volume, assumed as a functional unit, was that felled in the considered section by thinning at the age of 19 years and by the final cutting at the age of 32 years, for a total of 507 m^3*ha^1 (Figure 1) [29]. This amount was the physical stock of chestnut wood production and was also the basis for the carbon dioxide stock calculation.

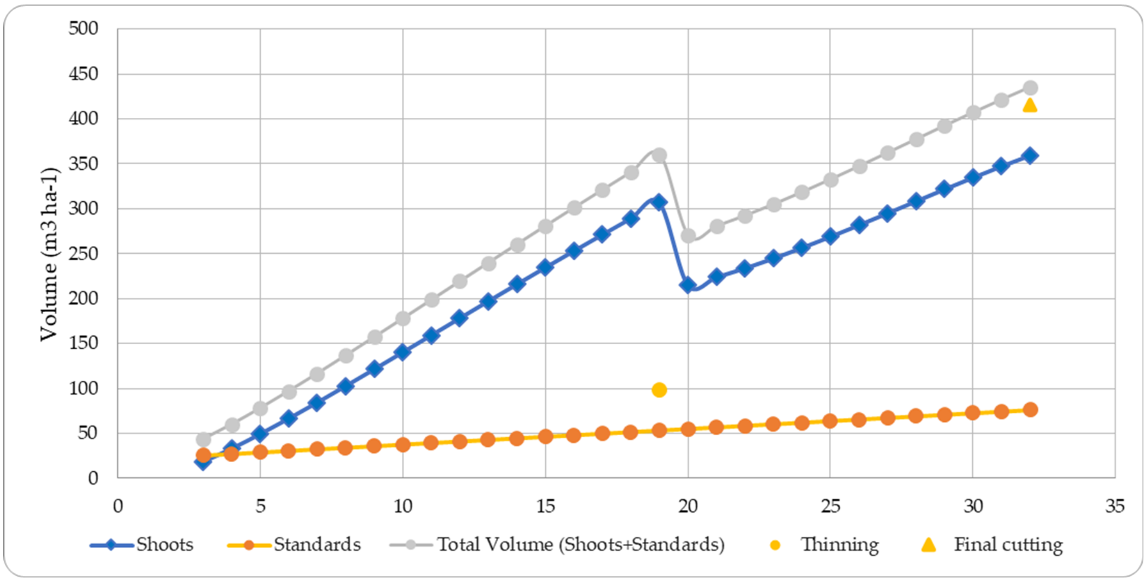

Figure 1. Chestnut growth and yield and wood fellings in the forest section considered in the case study.

2.3.2. Objective and Scope

The aim was to quantify CO_2 absorption and CO_2 emissions due to the activities developed along the supply chain of chestnut wood to the market of timber products (Figure 2). Four "gates" were identified and the Net–CDS calculated for each gate:

- Gate 1: at the end of forest harvesting, raw wood material was loaded onto the lorry;
- Gate 2: at the end of sawmill processing, SFCTs were loaded onto the lorry;
- Gate 3: chestnut timber products were allocated into the Rome market;
- Gate 4: chestnut timber products were distributed into the Northern Italy markets.

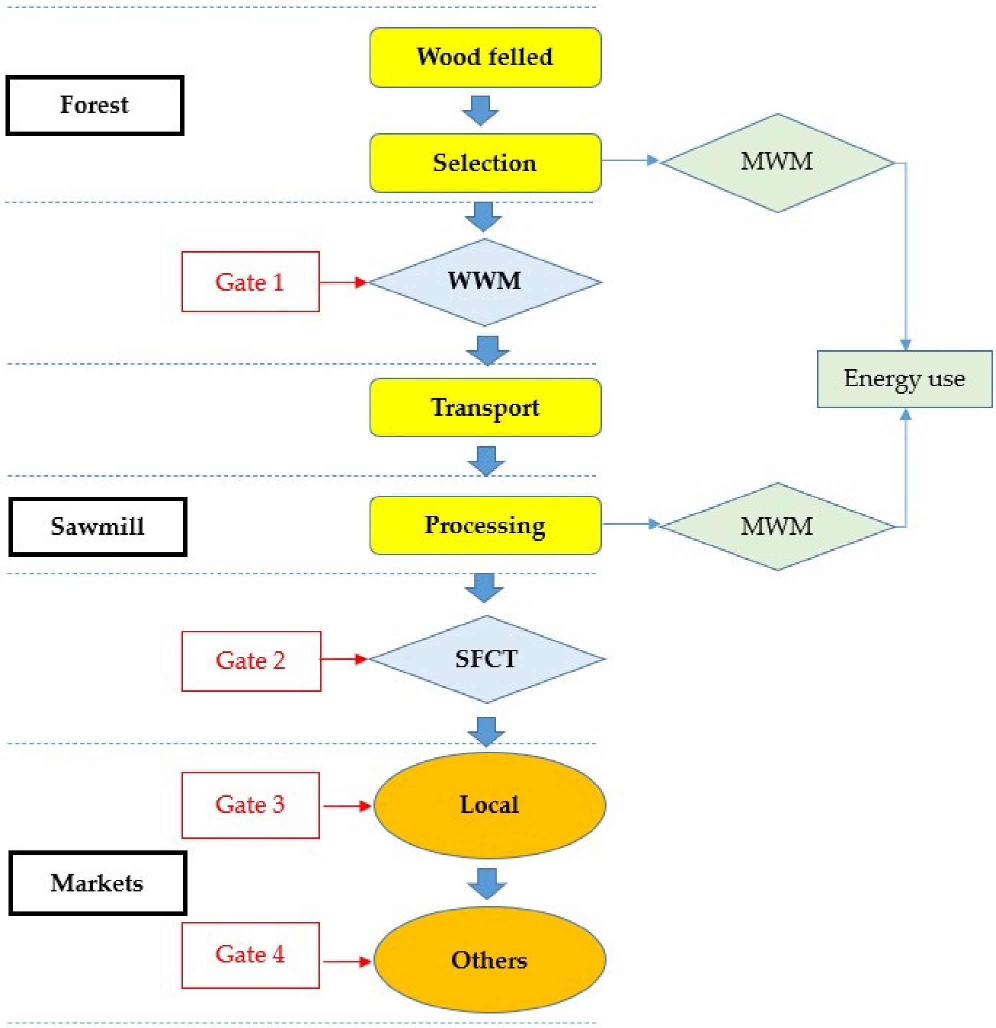

Figure 2. The supply chain of chestnut wood to the market of timber products. Legend: WWM: Workable Wood Material; MWM: Minor Wood Material; SFCT: Semi-Finished Chestnut Timber.

2.4. Calculation of CO_2

2.4.1. CO_2 Absorbed

The function by UNCCC was adopted for the quantification of the volume of CO_2 stored in chestnut wood [$V(CO_2)$]:

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

where:

ML—chestnut wood density in the dry state is 613 kg m^{-3} [38];
CC—carbon content in chestnut wood, equal to 0.48 [28,39];
$PA_{(CO_2)}$—molar mass of carbon dioxide equal to 43.99 M;
$PA_{(C)}$—molar mass of atomic carbon equal to 12.01 M.
The CO_2 stored from 1 m^3 of chestnut wood is 1079 $kgCO_2\ m^{-3}$.

2.4.2. CO_2 Emitted

The process from the supply chain of chestnut wood to the market of timber products is articulated in actions and sources (Table 2).

Table 2. Actions and CO_2 sources in the supply chain of chestnut wood to the market of timber products. Legend: FH: Forest harvesting; WS: Wood selection; TTF: Timber transformation; TTP: Timber transport; MC: Monitoring and controls; AA: Administrative activity.

		Actions					
		FH	**WS**	**TTF**	**TTP**	**MC**	**AA**
Sources	Harvesting machines	X	X			X	X
	Sawmill machines		X	X			X
	Handling and transport machines				X	X	X
	Other activities					X	X
	Working capital	X	X	X	X	X	X

Actions are distinguished between four operative actions and two general actions. The operative actions include:

- Forest harvesting: includes all activities that the logging company put into practice to fell the crop, according to the administrative authorities and regional forestry regulations.
- Wood selection: wood materials that arrive at the sawmill are unloaded into the various temporary storage areas. WWM and MWM are sorted by a cut-off machine; the operator selects the wood assortments, evaluating the best ones to go into the wood-working boxes, and the others to go to secondary assortments. Damaged or small fractions are destined for biomass; residual materials go directly to the biomass area for sale to the energy sector.
- Timber transformation: the WWM is directed to the most important processing lines; it is processed to make mainly sharp-edged products and then directed to the kiln for drying. Once the commercial humidity is reached, the boards are refined and are ready to be sold in the market of high-quality chestnut wood products. The residuals from refining are discarded and, along with the damaged boards, go into the biomass storage area.
- Timber transport: for internal transportation, a crane for the raw material and a forklift for the processed timber products are used. External timber transportation involves a 2-axle lorry to move the raw material from forest to sawmill, and a 3-axle lorry to move the SFCT products to the market. It is assumed that the articulated lorry returns to the starting point at the end of the delivery. General actions involve:
- Monitoring and controls: this refers to general activities which affect the forest ownership over time, such as supervision, control, monitoring and support by the forestry consultant.
- Administrative activities: the administration of the logging company, sawmill, and forest owner are included. CO_2 emissions are produced by electricity consumption for the functioning of machines (computers, telephones, printers, etc.) and to ensure employees work in a safe environment.

Emissions by general actions are assumed to be 2.50% of direct emissions (personal communication from expert). Sources that concern direct emissions from operational activities in which machinery, handling and transport equipment are used, while the fifth source concerns the emissions due to the production of working capital used. A description of the sources is outlined below:

- Harvesting machines: they are mainly chainsaws, tractors with winches, as well as the wood chipper; they are gasoline and diesel-powered tools.
- Sawmill machinery: the main ones are the cutting machine, the trimming machine, and the kiln. However, it also includes computers, multifunctional printers and other machinery used by the administration units. All machinery is usually powered by electricity.

- Handling and transport: lorries both for transporting the timber from forest to sawmill, and then from sawmill to market; there are also forklifts and cranes for internal timber handling. These vehicles are diesel-powered.
- Other activities: each year the forest owner carries out activities directly, such as monitoring, control and other forest management interventions. A forestry consultant is involved to project stand thinning and final cut.
- Working capital is the sum of the capital invested in the purchase of tools and the construction of structures for processing wood and the structure where forest, sawmill and logging company administration is carried out.

A general function for the calculation of GHGs is summarized below:

[Entity] × [Productivity] × [Consumption] × [Emission factor] × [Other parameters].

Table 3 shows the main parameters for the case of chestnut wood transformation and the relative units of measure, while Table 4 provides the unit of consumption and the emission factors used to quantify the CO_2 emitted from the working capital.

Table 3. Main parameters, abbreviations and units of measure used in the emissions calculation. Legend: CV: Chestnut Volume; HP: Hourly Productivity; HC: Hourly Consumption; KC: Kilometer Consumption; CC-F: Conversion Coefficient of Fuel; CC-EE: Conversion Coefficient of Electric Energy; T: Times; D: Distance; WH: Working Hours.

Category	Parameters	Udm
Entity	CV	m^3
Productivity	HP	m^3/h
Consumption	HC	L/h
	KC	L/km
Conversion coefficient	CC-F	$kgCO_2/L$
	CC-EE	$kgCO_2/KWh$
Other parameters	T	n.
	D	km
	WH	h

The production of working capital and tools generated CO_2. These emissions were estimated as follows. Assuming the total working capital (WK) issues expressed as a percentage (100%), these were broken down by the average lifetime of working capital (15 years) and the average volume of chestnut wood processed annually (CV_a) (20.000 m^3). The result was then multiplied by the total production (TP) (507 m^3), quantifying that CO_2 emissions amount to 16.7% of the total emissions so far calculated. Formally:

$$CO_{2\ \text{emitted}} = \left[\frac{WK_{(100\%)}}{WK_{(\text{years})} \times CV_a} \times TP \right] \quad (2)$$

where:

WK—working capital;
CC—average volume of chestnut wood annually processed; and
TP—total production of timber

2.4.3. Balance Sheet of CO_2

The framework of the balance sheet of CO_2 is composed of two tables referred to as absorptions and emissions. Absorptions shows the CO_2 fixed in the chestnut wood over time; when the trees are felled, the wood becomes the store where CO_2 is physically conserved. This amount can be considered the environmental stock. Emissions shows the

CO_2 emitted into the atmosphere as a consequence of the supply chain of chestnut wood to the market of timber products.

Table 4. Machines used in in the supply chain of chestnut wood to the timber products market. Legend: CSW: Chainsaw; TCR + W: Tractor + Winch; CRN + HyC: Crane + Hydraulic Clamp; WCP: Woodchipper; CTM: Cross-cut and Trimming-machine; KLN: Kiln; L-2AX: Lorry (2 axles); L-3AX: Lorry (3 axles); FKL: Forklift. (1) National Traffic Code states (a) for an articulated trailer L-2AX the limit of mass transportable is 22 tons (21.78 m^3); (b) from an articulated trailer L-3AX the limit of mass transportable is 26 tons (42.42 m^3).

Working Capital		**Energy Sources**	**Consuming**		**Emission Factors**	
			UdM	**Value**		
Harvesting machines	CSW	Petrol	L/h	1.13	$kgCO_2/L$	2.13
	TCR + W	Diesel	L/h	6.95	$kgCO_2/L$	2.66
	CRN + HyC	Diesel	L/h	5.28	$kgCO_2/L$	2.66
Sawmill machines	WCP	Diesel	L/h	6.24	$kgCO_2/L$	2.66
	CTM	Electric energy	kw/h	18.80	$kgCO_2/kwh$	0.55
	KLN	Electric energy	kw/h	23.51	$kgCO_2/kwh$	0.55
Handling and transport machines	L-2AX (1) L-3AX (1)	Diesel	L/km	0.29	$kgCO_2/L$	2.66
	FKL	Diesel	L/h	2.50	$kgCO_2/L$	2.66

The CO_2 stored in the raw material is subject to a reduction. There are two types of process that describe this regressive flow:

- Physical process: the CO_2 reduction follows the depletion of the volume of wood and the effects have been reported in the physical CO_2 balance sheet. Given the stock of CO_2 in the functional unit, this value is reported in the table of absorptions. Due to wood processing, secondary and residual wood material is discarded and the emission volume of CO_2 emitted is recorded in the emissions table. CO_2 decreases while CO_2 emitted into the atmosphere increases. Finally, in the table of absorptions, the CO_2 stored in the marketable WWM volume is shown.
- Formal process: a combination of the physical process of CO_2 with the CO_2 emitted due to the compensation of the greenhouse gases produced during the various transformation activities in the forest, in the sawmill and to transport the woody material. Results are reported in the formal CO_2 balance sheet. In the table of absorptions, the CO_2 stored in the WWM is recorded, while in the table of emissions, the amount of CO_2 consumed to offset CO_2 emissions is shown.

3. Results

3.1. Chestnut Wood Production

The flow of raw material in the transformation process is presented in Figure 2. The functional unit was 507 m^3. At the end of forest harvesting, there were 382 m^3 of MWM and 125 m^3 of WWM (Figure 3), i.e., the wood volume allocated in the market as SFCT products was just less than 25% of the total production.

3.2. Carbon Dioxide Stored

The total volume of CO_2 stored was 547,875 $kgCO_2$/ha (Table 5). This was distributed among shoots and standards for 448,457 $kgCO_2$ at the end of rotation, while 99,417 $kgCO_2$ was the amount in the stems felled at year 19 during the rotation.

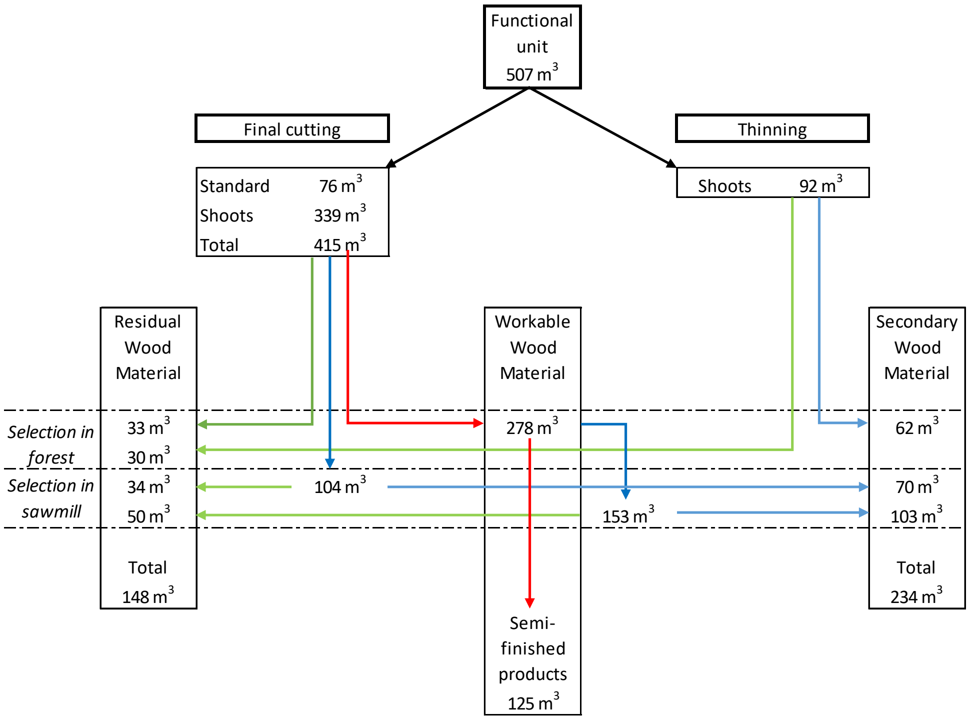

Figure 3. Functional unit and flow of raw chestnut wood material.

Table 5. Chestnut timber production and volume of CO_2 stored. Legend: WWM: Workable Wood Material, MWM: Minor Wood Material.

			MWM		WWM	Total
			Residual Wood Material	**Secondary Wood Material**		
Thinning cut	Volume	m^3/ha	30.39	61.69	0	92
	CO_2 stored	$kgCO_2/ha$	32,808	66,610	0	99,417
Final cut	Volume	m^3/ha	118	172	125,23	415
	CO_2 stored	$kgCO_2/ha$	127,409	185,839	135,210	448,548
Total	Volume	m^3/ha	148	233	125	507
	CO_2 stored	$kgCO_2/ha$	160,217	252,448	135,210	547,875

3.3. CO_2 Emitted

Stem felling and log sectioning were carried out by a chainsaw (both activities emitted 250 $kgCO_2$ each). Log concentration and extraction involved the tractor alone, generating emissions of 1567 $kgCO_2$. The separation and subdivision of the timber destined for sawmill and the resulting material were completed by a crane equipped with a hydraulic clamp, for which emissions of 651 $kgCO_2$ and 243 $kgCO_2$ respectively were estimated for WWM and MWM. The chipping phase of the woody material resulted in emissions of 30 $kgCO_2$. With a hydraulic clamp the poles and the shoots were loaded onto a lorry with, respectively, 651 $kgCO_2$ and 243 $kgCO_2$ emitted. The emissions were 3886 $kgCO_2$ to manage the raw material from final cutting (Table 6) and 774 $kgCO_2$ to manage the thinning output (Table 7). Overall, the management of raw wood material in the forest generated emissions of 4661.00 $kgCO_2$.

Table 6. Emissions from forest harvesting during the final cut. Legend: (1) CSW: Chainsaw; TCR + W: Tractor + Winch; CRN + HyC: Crane + Hydraulic Clamp; HyC: Hydraulic Clamp; WCP: Woodchipper; L-2AX: Lorry (2 axles); CV: Chestnut Volume; HP: Hourly Productivity; HC: Hourly Consumption; CC-F: Conversion Coefficient of Fuel; WH: Working Hours. (2) Loading of the truck is carried out directly by the chipper.

Sub Actions	Sources (1)	CV	HP	WH	HC	CC-F	CO_2 Emissions
		m^3	m^3/h	h	L/h	$kgCO_2/L$	$kgCO_2$
Felling	CSW	415.36	4.00	103.84	1.13	2.13	250
Sectioning	CSW	415.36	4.00	103.84	1.13	2.13	250
Concentration and logging	TCR + W	415.36	4.90	84.77	6.95	2.66	1567
Sorting (workable)	CNR + HyC	382.13	6.00	63.69	5.28	2.66	894
Chipping	WCP	33.23	18.20	1.83	6.24	2.66	30
Loading (Poles)	L-2AX + HyC (2)	103.84	6.00	17.31	5.28	2.66	243
Loading (Shoots)	L-2AX + HyC (2)	278.29	6.00	46.38	5,28	2.66	651
Loading (Chips) (1)	L-2AX	33.23					
Total emission							3886

Table 7. Emissions from forest harvesting during the stand thinning. Legend: (1) CSW: Chainsaw; TCR + W: Tractor + Winch; CRN + HyC: Crane + Hydraulic Clamp; HyC: Hydraulic Clamp; WCP: Woodchipper; L-2AX: Lorry (2 axles); CV: Chestnut Volume; HP: Hourly Productivity; HC: Hourly Consumption; CC-F: Conversion Coefficient of Fuel; WH: Working Hours.

Sub Actions	Sources (1)	CV	HP	WH	HC	CC-F	CO_2 Emissions
		m^3	m^3/h	h	L/h	$kgCO_2/L$	$kgCO_2$
Felling	CSW	92.08	4.00	23.02	1.13	2.13	55
Sectioning	CWS	92.08	4.00	23.02	1.13	2.13	55
Concentration and logging	TCR + W	92.08	4.90	18.79	6.95	2.66	347
Sorting	CRN + HyC	61.69	6.00	10.28	5.28	2.66	144
Chipping	WCP	30.39	18.20	1.67	6.24	2.66	28
Loading (Shoots)	L-2AX + HyC	61.69	6.00	10.28	5.28	2.66	144
Total emission							774

The next phase relates to moving the raw wood material from forest to sawmill (Table 8). Their volume amounted to 382 m^3 (278 m^3 for WWM and 103 m^3 for MWM) and 33 m^3 as residual wood material of the final cut. All this material was transported by a 2-axle lorry and covered an average distance of 40 km. For the 2-axle lorry 18 journeys were required (13 for WWM and 5 for MWM), as well as 2 journeys for the residual wood reduced to chips in the forest. The overall emissions were 1511 $kgCO_2$. The thinning outputs were 62 and 30 m^3 respectively for the secondary and residual material. The secondary material required 3 and 2 journeys for the chips, with total emissions of 299 $kgCO_2$. Overall transportation and unloading of all wood material emitted 1810 kg of CO_2.

Table 8. Emissions during transportation from forest to sawmill of poles, shoots and chips (for this action the chestnut fresh density adopted is 1010 kg/m^3) [40]. Legend: (1) HyC: Hydraulic Clamp; L-2AX: Lorry (2 axles); CV: Chestnut Volume; HP: Hourly Productivity; HC: Hourly Consumption; KC: Kilometer Consumption; CC-F: Conversion Coefficient of Fuel; T: Times; D: Distance; WH: Working Hours.

Sub Actions	Sources (1)	CV	HP	D&T		WH	HC		CC-F	CO_2 Emissions
		m^3	m^3/h	km	n.	Hours	Value		$kgCO_2$/L	$kgCO_2$
Transportation	L-2AX + HyC	61.69		40	3		L/km	0.29	2.66	93
Unloading			6.00			10.28	L/h	5.28	2.66	144
Transportation	L-2AX + HyC	103.84		40	5		L/km	0.29	2.66	154
Unloading			6.00			15.60	L/h	5.28	2.66	243
Transportation	L-2AX + HyC	278.29		40	13		L/km	0.29	2.66	401
Unloading			6.00			47.26	L/h	5.28	2.66	651
Transportation (1)	L-2AX	30.39		40	2		L/km	0.29	2.66	62
		33.23		40	2		L/km	0.29	2.66	62
Total emission										1810

In the sawmill, the timber is subjected to various processes (Table 9). The crane with hydraulic clamp loads the platform of the circular saw, which sorts the material and defines the production lines of each log. Later, the crane picks up the logs and allocates them to the subsequent processing machines, including the trimming machine from which the boards are obtained. The internal mobilization of logs produced emissions equal to 1303 $kgCO_2$, of which 651 $kgCO_2$ were for moving WWM to the circular saw and 651 $kgCO_2$ for moving the same material to the trimming machine. The circular saw and trimming machine produced 2761 $kgCO_2$. The most technologically advanced sawmills are generally equipped with a kiln for artificial drying. The timber was therefore placed in the kiln which, over just 45 days, reduced its humidity up to 13%, with quantified emissions equal to 12,316 $kgCO_2$. Regarding the fraction of the wood not intended for working uses, it was assumed that it was all (branches, tops, other scraps, blocks, and sawdust) sent to the chipping machine and marked as biomass for energy use. This process resulted in estimated emissions of 77 $kgCO_2$. The WWM was moved using a forklift in different stages and produced 128 $kgCO_2$ of emissions. Overall, the total emissions were 16,585 $KgCO_2$.

The final step was the transportation from the sawmill to the markets, using the 3-axle lorry with a consumption of 0.29 diesel/km, given a coefficient factor of 2.66 $kgCO_2$/L, obtaining emissions of 0.76 $kgCO_2$/km. Assuming that the primary chestnut timber market is located in Rome, where there is fervent restoration activity of historic buildings, the total emissions produced to reach the town from Colli Albani were 181 $kgCO_2$ (Table 10).

3.4. Balance Sheets of CO_2

3.4.1. Physical Balance Sheet

The 507 m^3 of chestnut wood was the stock of the functional unit and the CO_2 stored was 547,875 $kgCO_2$. The flow of material is reported in Table 11. At gate 1, the CO_2 stored in the functional unit showed a reduction of 45%. At gate 2, such reduction reached 75%. The CO_2 absorbed by MWM compensated for the CO_2 emitted, and therefore MWM did not produce any effect on the GHG amount. The contribution of chestnut wood to counteract climate change came from the 125 m^3 of SFCT products for a volume of 135,210 $kgCO_2$.

Table 9. Emissions during sawmill processing. Legend: [(1)] CRN + HyC: Crane + Hydraulic Clamp; WCP: Woodchipper; CTM: Cross-cut and Trimming-machine; KLN: Kiln; FKL: Forklift; CV: Chestnut Volume; HP: Hourly Productivity; HC: Hourly Consumption; CC-F: Conversion Coefficient of Fuel; CC-EE: Conversion Coefficient of Electric Energy; WH: Working Hours. [(2)] $kgCO_2/kwh$.

Sources [(1)]	CV	HP	WH	HC	CC-F&CC-EE	CO_2 Emissions
	m^3	m^3/h	h	L/h	$kgCO_2/m^3$	$kgCO_2$
CTM	283.57			18.18	0.55 [(2)]	2761
CRN + HyC	283.57	6.00	47.26	5.28	2.66	651
CRN + HyC	283.57	6.00	47.26	5.28	2.66	651
FKL	127.61	19.57	6.52	2.50	2.66	43
WCP	84.78	18.20	4.52	6.24	2.66	77
KLN	127.61		960	22,571.43	0.55 [(2)]	12,316
FKL	127.61	19.57	6.52	2.50	2.66	43
FKL	127.61	19.57	6.52	2.50	2.66	43
Total emission						16,585

Table 10. Emissions during the transport to market (city of Rome) of the SFCT products. Legend:L-3AX: Lorry (3 axles); FKL: Forklift; CV: Chestnut Volume; HP: Hourly Productivity; HC: Hourly Consumption; CC-F: Conversion Coefficient of Fuel; T: Times; D: Distance; WH: Working Hours.

Sub Actions	Sources	CV	HP	D&T		WH	HC		CC-F	CO_2 Emissions
		m^3	m^3/h	km	n.	h	Values		$kgCO_2/L$	$kgCO_2$
Transportation	L-A3AX	125		60	3		L/km	0.29	2.66	139
Unloading	FKL	125	19.57			6.40	L/h	2.50	2.66	43
Total emission										181

Table 11. Flow of chestnut wood material and physical balance sheet of CO_2. Legend: WWM: Workable Wood Material, MWM: Minor Wood Material.

Activities	Gate	Flow of Woody Material		Balance Sheet of Physical CO_2	
				sequestration	emission
		WWM	MWM	WWM	MWM
		m^3	m^3	$kgCO_2$	$kgCO_2$
Starting stock	0	507		547,875	
Forest management		278	229	300,467	247,408
Exit from forest	1	278	229	300,467	247,408
Sawmill process		125	153	135,210	165,257
Exit from sawmill	2	125	382	135,210	412,665
Rome market	3	125		135,210	

3.4.2. Offset Balance Sheet

The starting point of this balance sheet was the same as the functional unit used for the physical balance sheet: 507 m^3 and 547,875 $kgCO_2$. In addition to the CO_2 losses due to the physical processing of the wood, the balance included emissions due to the use of machines in the forest and sawmill, as well as those for wood handling and transport machines, other activities and production of working capital (Table 12).

Table 12. CO_2 emissions by sources and actions. Data expressed in $kgCO_2$. Legend: WWM: Workable Wood Material, MWM: Minor Wood Material; FH: Forest harvesting; WS: Wood selection; TTF: Timber transformation; TTP: Timber transport; MC: Monitoring and controls; AA: Administrative activity.

		Actions						Total CO_2 Emission for Sources
		Operative Actions			Other Action			
		FH	WS	TTF	TTP	MC	AA	
Sources	Harvesting machines	4355	305	0	0	3	116	4780
	Sawmill machines	0	2760	12,393	0	0	378	15,533
	Handling and transport machines	0	0	0	3240	29	81	3351
	Other activities	0	0	0	0	40	1	41
	Working capital	746	525	2122	555	12	96	4058
Total CO_2 emission for action		5101	3591	14,516	3795	85	674	27,765

Net of MWM emissions, at gate no. 1 (Table 13), the real CO_2 stored in chestnut WWM was 300,466 $kgCO_2$. However, part of this budget was used to offset emissions of machines used during harvesting and timber sorting, transport and processing in sawmill for overall emissions equal to 27,005 $kgCO_2$. Considering the other actions, such as monitoring and controlling forests during the rotation and administrative activities, emissions equal to 760 $kgCO_2$ needed to be added. At gate 2, the overall emissions of forest and sawmill activities were 27,765 $kgCO_2$ and the formal CO_2 stored in the SFCT product was 107,444 $kgCO_2$. However, SFCT products must be placed on the market. The market of Rome is the closest to the Colli Albani, with a distance of 30 km (return trip 60 km) (Gate 3). The reduction rate for each kilometer travelled to reach other markets was 0.77 $kgCO_2$/km, net of the emissions due to the lorry loading.

Machines were the source of the highest emissions, accounting for 56% (Figure 4), while the timber processing in the sawmill was the action that accounts for the highest proportion of emissions, at 53% (Figure 5). These high percentages derived in both cases from the use of the kiln that injected 12,394 $kgCO_2$ into the atmosphere, to reduce the wood humidity to 12%–13%.

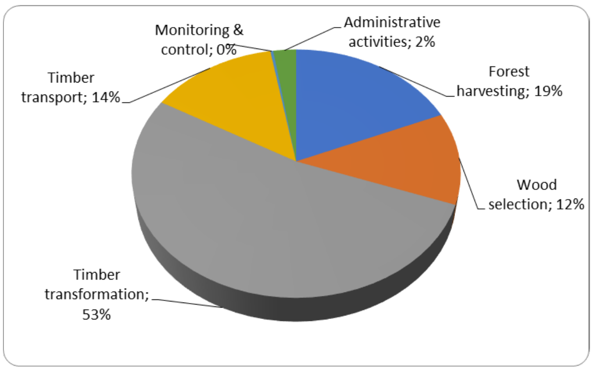

Figure 4. CO_2 emissions by types of actions.

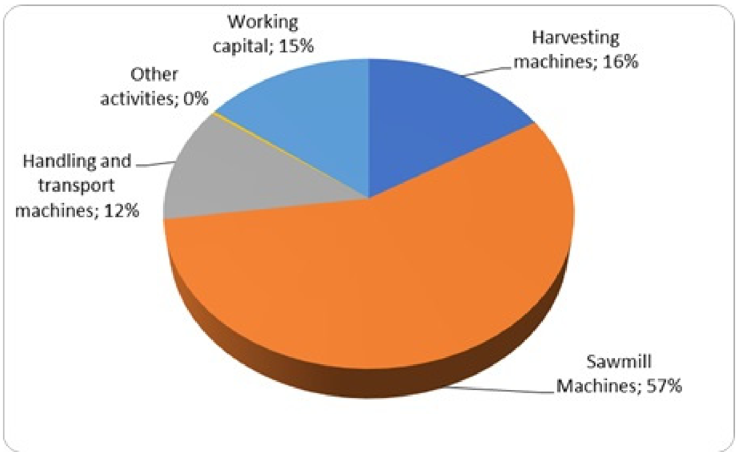

Figure 5. CO_2 emissions by types of sources.

Table 13. Flow of chestnut wood material and formal balance sheet of CO_2. Legend: (1) Direct, in-direct and other activities; WWM: Workable Wood Material, MWM: Minor Wood Material.

	Gates	Flow of Woody Material		Balance Sheet of Formal CO_2			Net-Carbon Dioxide Surplus
				Absorption	Emission		
		WWM	MWM	WWM	MWM	Activities (1)	
		m^3	m^3	$kgCO_2$	$kgCO_2$	$kgCO_2$	$kgCO_2$
Functional unit	0	507		547,875			547,875
Forest management		278	229		247,4084	5102	
Timber selection						3591	
Gate 1	1	278	229	300,467	247,408	8693	291,774
Sawmill process		125	153	135,210	165,25	14,516	
Timber transportation						3796	
Other activities						86	
Administrative activities						677	
Gate 2	2	125	382	135,210		19,073	107,444
Transport to Rome						141	
Gate 3 (Roma market)	3	125				181	107,263

4. Discussion

Timber is considered an effective alternative to carbon-intensive materials [41]. In its latest forestry strategy [42], the EU stressed the importance of using wood as one pillar of the forest-based bioeconomy and as a viable means to combat climate change. In particular, the EU focused on the concepts of the optimal use of wood, the importance of timber production from European forests compatible with environmental values, and the use of wood products with a long lifetime. Concerning wood production, the focus is generally mainly on conifers [18]. However, there are circumstances where broadleaf production has better environmental performance than conifers.

The high fertility of volcanic soils in the Colli Albani area explains both the large production capacity of chestnut wood by each coppice rotation (507 m^3/ha), and its high specific density (613 kg/m^3), 5% more than the standard density [43,44]. These parameters are responsible for chestnut wood's high CO_2 conservation capacity, which is 547,875 $kgCO_2$. However, a critical paradox has been highlighted: the wood volume destined for products with a long lifetime (WWM) is 25%, while the largest part of the material (MWM) has a short lifetime [29,45].

The above figures have a strong impact on the corresponding CO_2 balance sheets. The physical balance of CO_2 shows that, compared to a volume of SFCT products of 125 m^3 and Net-CDS equal to 135,210 $kgCO_2$, the relevant amount of 382 m^3 (and relative 412,664 $kgCO_2$) does not contribute to the fight against climate change.

The formal balance sheet of CO_2 accentuates the above figures: according to the 125 m^3 of marketable WWM, the CO_2 used for contrasting climate change is 107,444 kg, with a Net-CDS equal to only 20% of the initial CO_2 stock sequestered by the trees in the functional unit. However, the transport onto the market affects the formal balance sheet of CO_2. The conserved CO_2 is reduced by 2.31 $kgCO_2$/km. At the market in Rome, the CO_2 conserved is 107,263 $kgCO_2$, and assuming the placement of SFCT products onto other extra-regional markets (gate 4), the Net-CDS continues to shrink progressively ([6). For the formal CO_2 balance, 1 m^3 of raw material stores 1080 $kgCO_2$ and it is subject to a continuous reduction process according to the relative emissions along the supply chain. At the Rome market, the WWM has a formal volume of CO_2 per unit of volume of 856 $kgCO_2/m^3$, a reduction from the initial stock of 22%. If WWM is transported to other markets outside the Lazio Region, for example to the Trento market (+1280 km, return trip), it registers a further reduction of 0.3% per 100 km, for a total of 25%, compared to the CO_2 stored at the felling in the forest (Figure 6).

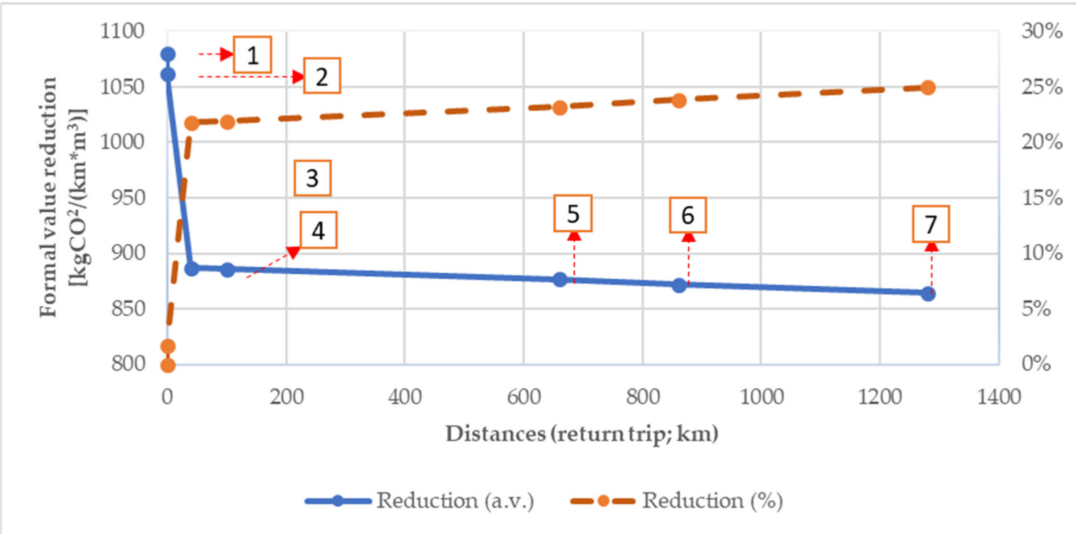

Figure 6. Reduction of Net-CDS of chestnut wood by the distance to the markets (1 = forest; 2 = forest temporary repository; 3 = sawmill; 4 = market of Rome; 5 = market of Florence; 6 = market of Bologna; 7 = market of Trento).

To involve wood production as a countermeasure against climate change, the results of the physical balance sheet would lead to an overestimation of its contribution. Instead, the formal balance sheet makes it possible to consider the role of processing activities to transform wood into marketable products.

Chestnut has long been employed in the construction of historical buildings, and in the last two decades, many initiatives have been adopted to boost its use for timber. Projects have involved topics such as the wood's physical—chemical—mechanical characteristics [46], strategies for improving chestnut forest management [47], reducing ring shake defects [48], and for enlarging the range of SFCT products [20]. Despite the amount of CO_2 offset, this study confirms the role of chestnut wood in combating climate change and this is a new value added to the chestnut wood.

Currently, chestnut wood valorization is an imperative target for both the mountain and national economies. The data obtained from the case study highlight that just 25% of raw chestnut wood has been exploited to produce long-lifetime goods, and the formal volume of CO_2 stored from SFCT is only 20% of the CO_2 stored from the functional unit. Literature [26–29] develops the LCA aspect to a functional unit of 1 m^3 of timber. However, in this study, a holistic approach was adopted. In the innovative "cradle to multiple gates" approach, the functional unit was the total volume of wood generated by an area of 1 ha throughout the 32-year life cycle. Offset emissions are, firstly, those from the wood processing cycle to obtain SFCTs and then all emissions related to the MWM's secondary processing cycles, as well as emissions related to administrative activities and those related to the production of working capital.

5. Conclusions

LCA is a well-established tool that stands out for its flexibility. The "cradle to multiple gates" approach adopted here allowed the analysis of the whole chestnut wood supply chain for a typical, representative case study in Central Italy, illustrating the dynamics of stored CO_2 along the chain and the corresponding Net-CDS.

In recent decades, the global political system has urged economic operators to contribute more efficiently to the fight against climate change. The globalization of markets and the standardization of goods mainly favour consumer products on an international scale, to the detriment of local production. The timber market is one example of this phenomenon. The physical-chemical-mechanical characteristics of mainly coniferous species are widely recognized internationally, while the local production of hardwood, including chestnut, has been largely marginalized, despite having similar or superior characteristics.

This study provides a new indicator, the Net-CDS, that highlights the ability of wood to fix CO_2, net of emissions due to wood loss during processing, that used by working capital, and other direct and indirect emissions. Moreover, given the aim of increasing the competitiveness of chestnut wood on the market and considering the entire supply chain of chestnut wood processing, there are many opportunities to improve its Net-CDS. Specific policy should promote initiatives related to:

(a) supporting forest management through an extension of the rotation in order to obtain crops with greater stem size and investing resources in thinning management to improve the quality of final wood production, as well as expanding the areas of the chestnut coppices managed by intervention that favor the quality of wood; and

(b) reducing the ecological footprint of the supply chain of chestnut wood to the timber products market by considering that fossil fuels are the main power source, and that the logging companies and sawmills of Colli Albani do not traditionally use low-CO_2-emission energy sources. To this end, suggestions include the use of battery/electric chainsaws and bio-based fuels for harvesting machinery; the use of residual wood to produce electricity for fixed electric machines and the replacement of fossil fuels with bio-based fuels for mobile tools in the sawmill; and the recovery of biomass and wood residues in a circular economy chain for the production of energy.

From the point of view of the market, the exploitation of the Net-CDS may influence both supply and demand. The Net-CDS promotes the production of wood products with long-term uses and can contribute to qualifying for the environmental standards of wood products such as EMAS certification, Ecolabel, etc. It can also be used to qualify for the environmental standards of local wood production. Furthermore, in a competitive market, the Net-CDS can be used for comparative analysis between alternative wood products, between wood products from different tree species, and between woody and non-woody products. Considering the first two hypotheses and assuming that trees have the same physical, chemical and mechanical standards, as well as price, the Net-CDS guides the rational consumer to purchase wood products with the highest Net-CDS. From this perspective, the Net-CDS indicator is easy to use for qualifying forest tree species, and it can have positive effects on forest management approaches, wood processing and marketing conditions as a part of the fight against climate change.

Author Contributions: F.C. has been scientific coordinator and has taken care of the research conceptualization and methodology; P.C. has carried out the supervision and has taken care of the writing-revision and modifications; M.H. has taken care of the formal analysis, writing-revision and modifications; F.B. has taken care of the data collection, analysis, and the writing of the original draft. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: All data used in the manuscript are reported in the text.

Acknowledgments: The authors are grateful to forest consultants, timber companies and sawmills who provided useful information and technical data.

Conflicts of Interest: The authors declare no conflict of interest.

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