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Soil Organic Carbon Stock Assessment for Volunteer Carbon Removal Benefit: Methodological Approach in Chestnut Orchard for Fruit Production

Mauro De Feudis [1,*], Gilmo Vianello [2] and Livia Vittori Antisari [1]

[1] Department of Agricultural and Food Sciences, Alma Mater Studiorum-University of Bologna, Viale Fanin 40, 40127 Bologna, Italy; livia.vittori@unibo.it
[2] Accademia Nazionale di Agricoltura, Via Castiglione 11, 40124 Bologna, Italy; gilmo.vianello@unibo.it
* Correspondence: mauro.defeudis2@unibo.it

Abstract: The implementation of a protocol for supporting a reliable soil C market is needed. This paper aims to propose a methodology for evaluating soil organic C (SOC) stock changes for the C credit market. A 15-year-old chestnut orchard (CO) and a chestnut coppice (CC) as reference land were selected in the northern part of the Apennine chain (Italy). The CO is the result of the CC conversion carried out in 2005. The soil sampling by pedogenetic horizons till parent material was carried out in 2005, 2010, 2015 and 2020 in CO and in 2005 and 2020 in CC. For each sample, the concentration and stock of the total SOC and of the most recalcitrant SOC form were estimated. Unlike the CC, in CO, an increase over time of SOC stocks was observed throughout the entire soil profile indicating the suitability of CO for C credit gaining. Most of the SOC was stored within the deepest soil horizon. The methodology can be considered eligible for the C credit market because, replicable, the CO was intentionally realized by humans after 1990, and the additionality was evaluated. Moreover, soil functionality was considered through the evaluation of SOC forms and of the pedogenetic horizons.

Keywords: land use; additionality; pedogenetic horizon; organic carbon forms

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1. Introduction

The Paris Agreement, signed in 2015 by the member states of the United Nations Framework Convention on Climate Change (UNFCCC), contains policy obligations related to the actions against climate change for all countries of the world [1]. The main goal of the agreement is to keep the global mean air temperature increase below 2 °C compared to pre-industrial levels.

Driven by the European Green Deal, the European Mid-Century Strategies foresee net zero-greenhouse gas (GHG) emissions by 2050 [2], highlighting that CO_2 emissions must be equal to or lower than the CO_2 removal from the atmosphere. Soil, forests, and oceans are the main natural carbon sinks that could be capable of sequestering between 9.5 and 11 gigatons of CO_2 per year. This is still not enough to offset the roughly 38 gigatons of CO_2eq globally emitted [3]. To cope with this problem, technological solutions have been proposed to "sequester" CO_2 both in agricultural and industrial sectors, whose effectiveness is still a field of debate [4].

In terrestrial ecosystems, carbon immobilization is mainly carried out by soil. Globally the organic C stored within soils is about 2.3 and 3.5 times greater than the C in the atmosphere and in all living terrestrial plants, respectively [5].

According to Orgiazzi et al. [6], in the European framework, the results of the land use and coverage area frame survey (LUCAS) project highlighted that agriculture soils had lower organic C amount (17.8 g kg^{-1}, on average) than grassland and woodlands (on average 40.3 and 77.5 g kg^{-1}, respectively). Moreover, the LUCAS project estimated that soils containing less than 2% organic carbon are about 75% of all European cultivated lands [7–9].

The overall loss of organic C from soils has raised many concerns [10–13]. In this regard, soil conservation and restoration practices appear to be very important in limiting organic C loss [14–16]. Several soil management proposals have been promoted with this purpose [17–19], and most of them also turn out to be climate change adaptation measures [20].

The land use, land use change and forestry (LULUCF) regulation (Reg. EU 842/2018) was adopted in the framework of energy and climate policy (2021–2030) with the main aim of reducing EU CO_2 emissions by at least −40% by 2030 compared to 1990 [2]. According to the UNFCCC, LULUCF is a designation encompassing a broad range of activities, including agricultural and forest land management, agricultural land conversion, afforestation, reforestation, and avoided deforestation.

In this view, where many industrialized countries are taking measures to reduce their net emissions of GHGs, a carbon credit-trading scheme was adopted [21]. Generally, this trading involves corporations that buy C credits to offset their own C emissions elsewhere and sellers like landholders and natural ecosystem managers who deliver ecosystem services and commodities that are translated into C credits [22]. A carbon market needs public or private funding to change land management or use and to reduce GHG emissions or increase carbon sequestration and storage [23].

Over the last decade, the potential for sequestering C in agricultural and forestry sinks to generate C credits has received increased attention from policymakers, government and non-government organizations, private companies, and farm managers [22]. The interest in C sequestration mostly regarded soil [24–26]. However, nowadays, much uncertainty still remains about soil C estimation because it cannot be measured in the same way as point-source industrial emissions or the creation of above-ground biomass in forests. Therefore, the implementation of a measurement protocol for supporting a reliable soil C market is an important issue remaining to be resolved. In addition, despite bold claims about the potential of soil to sequester C, the science is still mixed on whether soil carbon sequestration is a viable climate solution, particularly in terms of the quantity of carbon that can be stored and for how long. Further, soil is a natural resource whose functions (i.e., C sequestration) strongly depend on pedogenetic factors such as land use, morphology, climate, geology and soil features. Therefore, to ensure that the soil carbon credits are high-quality and the practices that generate them are environmentally beneficial, the credits must undertake a thorough vetting process. Specifically, valuable protocols related to soil sampling and C measurements must be established; otherwise, the soil C market could become inhabited by loopholes that allow polluters to continue to pollute.

1.1. Land Use

The enhanced attention to the role of soil in the C market could push governments and companies to find lands to sequester carbon to avoid making real cuts to their CO_2 emissions. In this sense, it is important to highlight the different potential of land use to store carbon [27,28]. Plenty of literature has reported the more significant role of soil under grasslands and forests in storing organic carbon compared to farmlands (e.g., Refs. [29–31]). The relatively low soil C storage of farmlands is attributed to the intensive agricultural practices, which are generally characterized by both low organic C and high N input promoting soil organic C loss by mineralization processes [15]. Because of the major role of natural lands (e.g., forestlands, grasslands, and wetlands) in soil organic C sequestration, the C market could create incentives for land-grabbing [32]. To avoid land-grabbing by governments and companies that want to apply their C sequestering projects in non-anthropic lands, the concept of additionality must be taken into account. Specifically, the additionality is the additional soil C sequestration related to the project compared to the C sequestration that can be observed under business-as-usual conditions [33]. This fact suggests the necessity to measure organic carbon concentrations also in "reference lands", namely lands with similar features and management to those under the C credit market but not affected by the project, to grant only the C sequestered through the application of the project.

Although natural ecosystems are currently storing large amounts of soil organic carbon, agricultural soils have a higher potentiality to play such function compared to the soil of natural ecosystems, having lost in the past decades an important portion of their original soil organic carbon [34]. Because of this high potentiality, the C market should not be applied for land use change projects to avoid risks of food insecurity due to agricultural land reductions.

1.2. Climate

The climate, in terms of mean air temperature, is a key driver of soil organic C, whose accumulation is promoted where low temperatures occur [35]. In fact, more intense mineralization processes occur in warm areas promoting soil organic C loss [36,37]. Because of this, a larger soil organic C storage can be observed at higher latitudes and altitudes compared to the lower ones [36,38–40]. The major effect of soils in cold areas to store C might cause investments in forestry and agriculture to be addressed to improve their sustainability only at the northern latitudes. Further, the larger soil organic C storage in cold areas compared to warm ones might cause inequity within the C market system. Specifically, the C market will be more economically advantageous for landholders of cold areas.

1.3. Organic Carbon Forms

Soil organic C (SOC) comprises a large range of compounds characterized by a variable susceptibility to degradation. Some components are rapidly decomposed, whilst others decompose more slowly and accumulate in the soil over time. In this context, it is well recognized the major role of the physical protection mechanisms for SOC preservation [41,42]. Soil organic compounds can be physically protected within aggregates or adsorbed on the surfaces of mineral particles forming organo-mineral complexes [43–47]. These two mechanisms can shield organic compounds from microbial attack because of a physical barrier between the organic compounds and the decomposer. The processes of the inhibition of microbial access to the organic substrate allow the preservation of SOC for thousands of years [48]. In fact, the physically-protected organic C can have turnover times up to 1000 times longer (reaching 10,000 years) than the labile organic carbon [49,50]. Therefore, to get C credits, the physically-protected organic C forms should be considered. However, since soil is a living body [51], the practices addressed to accumulate SOC must also preserve the labile organic C forms. In fact, the labile organic compounds fuel the soil food web and affect nutrient cycles and many biologically related soil properties [52] other than contributing to the accumulation of soil organic C [53]. Further, the labile organic compounds are feed for soil microorganisms [54], which are recognized as an important precursor to the formation of stable SOC [55–57].

1.4. Soil Sampling

Appropriate sampling strategies and sampling units are prerequisites for the generation of robust soil organic C data. The sampling approach should reflect the variation of the target soil property (i.e., organic C) in the area under investigation. This is further emphasized by the complexity of the soil, whose properties are controlled by interactions of time, climate, geomorphology, parent materials, vegetation, and humans, which have not been well quantified [58]. To get C credits, temporal samplings are required though this sampling approach must cope with the soil variability, which could be solved by georeferencing the sampling points [59]. Although the natural ecosystems (e.g., forestlands and grasslands) are recognized to store more SOC compared to farmlands [29–31], to have comparable data about C accumulation/loss, the organic horizons should be excluded for the calculation of C credits. In fact, although the organic horizons have higher organic C concentrations compared to mineral ones [60,61], they are lacking in farmlands and their mass is characterized by seasonal variations [62].

Recently it has been demonstrated that the sampling by pedogenic horizon is considered more suitable compared to fixed depth layers in organic C assessment because it allows us to gain additional information on the nature of the SOC and the connections between the environment and C dynamics [61]. However, since the C credit market related to soil merely focuses on the amount of C accumulated/lost within a certain soil depth interval, soil sampling by fixed depth intervals can be considered optimal, mainly in an agricultural context, because of its ease of execution and cost-effectiveness.

Another issue related to soil sampling concerns the sampling depth. Several papers reported the major role of deep soil layers in storing C [63,64] and the higher amount of stable forms of C in the subsoil than in the topsoil [46,65]. However, at the global scale, most of the information and studies related to organic C stock refer to the upper 0.3 m of the soil profile [66–68]. A shallow sampling depth is usually chosen for financial and practical reasons [69]. Thus, to allow cheap samplings and easy comparisons with other soils, C credit can concern the topsoil layer.

1.5. Aim of the Study

In the framework of C sequestration, the aim of the present work was to propose a methodology for evaluating SOC stock changes for the voluntary C credit market. The proposed methodology was tested on a 15-year-old chestnut (*Castanea sativa* Mill.) orchard located in the Northern part of the Apennine chain (Italy) resulting from the conversion of a chestnut coppice after clear-cutting.

2. Materials and Methods

2.1. Area of the Study Case and an Example of Soil Sampling Model

In the present work, an area covered by chestnut (*Castanea sativa* Mill.) plants within the municipality of Alto Reno Terme in Italy was considered (Figure 1). The area was within the National Centre for the Study and Conservation of Forest Biodiversity, located at about 700 m above sea level and had a cold-temperate climate, with a mean annual precipitation of 905 mm and a mean annual air temperature of 12.2 °C (Ref. [70]). The soil was classified as Leptic Skeletic Dystric Regosol (Loamic, Humic) according to the World Reference Base [71].

Within the study area, a 15-year-old chestnut orchard for fruit production (CO) as testing land and a chestnut coppice (CC) as reference land (business-as-usual conditions) were selected (Figure 1). In 2020, the CC and CO had a density of 140 and 150 living stumps ha^{-1}, respectively. The CO is the result of the conversion of CC carried out in 2004. Specifically, the CC was clear-cut in 2004, and the chestnut stumps of the clear-cut trees were grafted in 2005. In CO, the plants were pruned yearly, and the plant residues were shredded onto the soil's surface. Instead, in CC, the stools are cut roughly every 20–25 years, while the understory is removed yearly and left on the soil's surface. The choice to take into account the CC to CO conversion was based on the growing interest of farmers to restore chestnut stands [70]. Within CO and CC, a target area 1 ha wide was identified, which was theoretically divided into 4 plots 2500 m^2 wide. Within each plot, four georeferenced soil profiles were dug till parent material, and each identified soil mineral horizon was sampled. For each plot, soil samples coming from similar soil horizon types were mixed to obtain a composite sample.

In CO, the soil sampling was performed at orchard establishment (in 2005; T0) and 5 (T1), 10 (T2) and 15 (T3) years later. Whilst, because of the unchanged land use, in CC, the sampling was performed in 2005 and 2020. For each sampling time, soil profiles were dug at about 0.5–1.0 m apart from the previous ones. All the samplings were carried out in July.

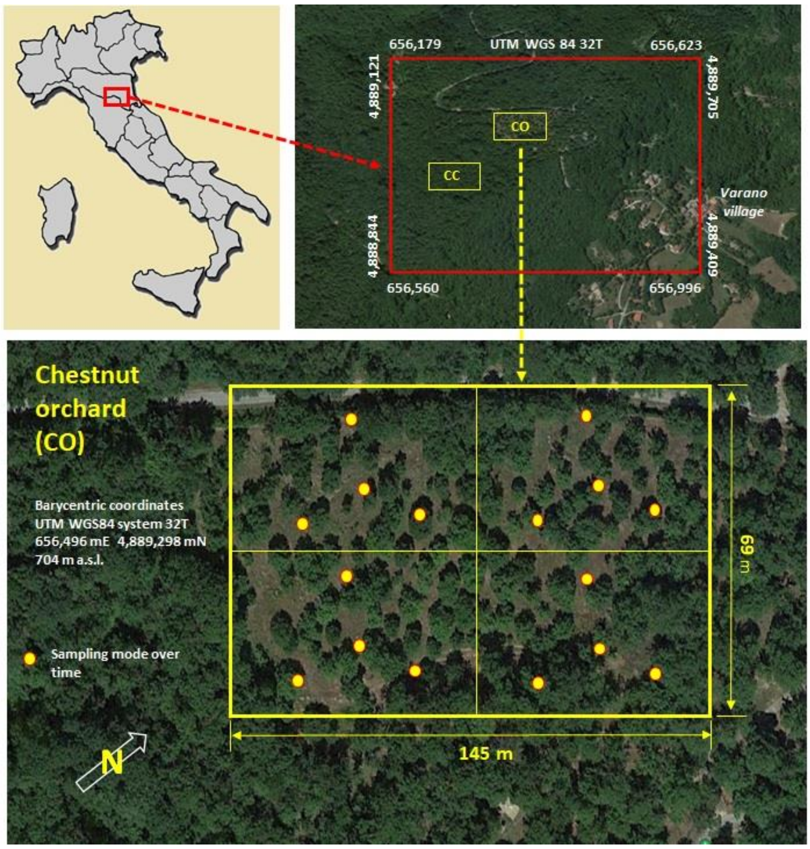

Figure 1. Chestnut (*Castanea sativa* Mill) coppice (CC) and orchard for fruit production (CO) located in the "National Centre for the Study and Conservation of Forest Biodiversity" (Northern Apennines, Alto Reno Terme, Italy), and soil sampling design applied in both chestnut stand types.

The litter layer (Oi) and the organic horizon Oe have not been taken into account for their possible transformations during the seasonal cycles [72–74] since they are mostly formed by non-stable organic C forms, which would bias the calculation of organic C stocks. Their mean thickness and organic C content are reported in Table 1.

In addition, undisturbed soil samples were collected by steel cylinders for the determination of the bulk density (BD). The collected samples were oven-dried at 105 °C, and then their mass was weighed. Because of the absence of skeleton in both sites, the bulk density was calculated by dividing the dry weight at 105 °C by the volume of the cylinder.

Table 1. Thickness and organic C content of Oi and Oe horizons in a 15-year-old chestnut orchard for fruit production (CO) and chestnut coppice (CC) recorded in July from 2005 to 2020. The organic C content was measured by the loss-on-ignition (LOI) method, according to Schulte and Hopkins [75] and Cambardella et al. [76].

Site	Year	Horizon	Thickness	Organic C
			cm	g kg^{-1}
CO	2005	Oi	0.3	369
		Oe	0.5	196
	2010	Oi	0.5	380
		Oe	1.0	160
	2015	Oi	0.9	388
		Oe	0.5	212
	2020	Oi	1.2	396
		Oe	1.6	207

Table 1. *Cont.*

Site	Year	Horizon	Thickness	Organic C
			cm	g kg^{-1}
CC	2005	Oi	1.9	404
		Oe	3.0	112
	2020	Oi	2.0	409
		Oe	2.5	118

2.2. Soil Organic Carbon Estimation

All soil samples were air-dried and sieved through a 2 mm mesh to divide skeleton (Ø > 2 mm) from the fine earth (Ø ≤ 2 mm).

The different forms of organic carbon were determined by the loss-on-ignition (LOI) method, according to Schulte and Hopkins [75] and Cambardella et al. [76]. Specifically, 6 g of fine earth was placed in ceramic crucibles and heated at 105 °C for 12 h to remove soil moisture and at 160 °C to remove the interstitial water. The soil organic matter (SOM) was determined at 450 °C, while the recalcitrant organic carbon (ROC) was determined at 550 °C. Two replicates per sample were analyzed in analytical assays to reduce the analytical error.

The organic C forms were calculated as follows:

$$\text{Interstitial water }\% = \frac{\text{P105}^\circ\text{C} - \text{P160}^\circ\text{C}}{\text{P105}^\circ\text{C}} \times 100$$

$$\text{Soil organic carbon (SOC) }\% = \frac{\text{P160}^\circ\text{C} - \text{P450}^\circ\text{C}}{\text{P105}^\circ\text{C}} \times 100 \times \frac{1}{1.72}$$

$$\text{Recalcitrant organic carbon (ROC)} = \frac{\text{P450}^\circ\text{C} - \text{P550}^\circ\text{C}}{\text{P105}^\circ\text{C}} \times 100$$

The stock of organic C and recalcitrant organic C (SOCstock and ROCstock, respectively) were calculated by the following equation (FAO, 2019):

$$\text{Stock} = \text{C} \times \text{BD} \times \text{thickness} \times (1 - \text{sk}) \times 10$$

where stock is SOCstock or ROCstock expressed as Mg ha^{-1}, C is SOC or ROC content expressed as g kg^{-1}, BD is bulk density expressed as Mg m^3, thickness refers to the 0–30 cm depth or horizon thickness expressed as m, and sk is the volume of skeleton expressed as a percentage.

3. Results

In 2005, the soil under CO had weaker soil development compared to CC, showing the lack of B-like horizons and a thinner A horizon. Conversely, the C horizon showed a larger thickness under CO than under CC. In addition, the A horizon thickness in CO increased from T0 to T1, while the C horizon thickness did not change over time (Table 2). Further, the results showed a higher stock of both SOC and ROC within the deepest soil horizon. No over-time changes in horizons' thickness were observed in CC. The SOCstock of CO showed an over-time increase, with values that were 108% higher in 2020 compared to 2005 (Table 3). Conversely, the SOCstock in CC did not change from 2005 to 2020 (Table 3). Noteworthy, although at T0, the CO had a lower SOCstock compared to CC, at T3, the SOCstock values resulted in being higher in CO than in CC. Similar to SOCstock, an over-time increase of ROCstock within the 0–30 soil interval depth was observed under CO (116%), whilst the increase under CC was negligible (Table 3).

Table 2. Values of thickness and bulk density (BD), mean ± standard of total organic carbon content (SOC), recalcitrant organic carbon content (ROC), SOC stock (SOCstock) and ROC stock (ROCstock) of the pedogenic horizons of soil profiles dug from 2005 to 2020 in a 15-year-old chestnut orchard for fruit production (CO) and a chestnut coppice (CC).

Site	Year	Horizon	Thickness	BD	SOC	ROC	SOCstock	ROCstock
			cm	g cm^{-3}	g kg^{-1}	g kg^{-1}	Mg ha^{-1}	Mg ha^{-1}
CO	2005	A	2.3	1.007	73.9 ± 2.1	0.46 ± 0.07	16.7 ± 0.5	0.11 ± 0.02
		AC	6.0	1.022	32.5 ± 1.7	0.41 ± 0.06	19.9 ± 1.0	0.25 ± 0.04
		C	21.7	0.998	20.3 ± 1.6	0.74 ± 0.11	44.2 ± 3.4	1.61 ± 0.24
	2010	A	4.7	1.018	75.2 ± 10.3	0.77 ± 0.09	35.8 ± 4.8	0.37 ± 0.04
		AC	4.3	1.015	43.8 ± 9.8	0.67 ± 0.04	19.2 ± 4.4	0.29 ± 0.02
		C	21.0	0.999	33.0 ± 7.6	0.85 ± 0.08	69.2 ± 2.5	1.78 ± 0.17
	2015	A	3.3	1.024	86.6 ± 2.9	0.87 ± 0.09	29.3 ± 0.9	0.29 ± 0.03
		AC	5.5	1.016	46.6 ± 9.7	0.89 ± 0.11	26.0 ± 3.9	0.50 ± 0.06
		C	21.2	0.987	37.2 ± 8.8	0.94 ± 0.17	77.8 ± 18.5	1.97 ± 0.36
	2020	A	4.7	1.018	94.8 ± 9.9	0.98 ± 0.05	45.4 ± 4.7	0.47 ± 0.02
		AC	6.7	1.019	62.1 ± 5.3	1.08 ± 0.13	42.4 ± 3.6	0.74 ± 0.09
		C	18.6	0.979	43.1 ± 8.3	1.66 ± 0.31	78.9 ± 15.2	3.04 ± 0.57
CC	2005	A1	6.0	1.005	76.3 ± 6.2	0.52 ± 0.09	47.0 ± 1.8	0.16 ± 0.03
		A2	9.0	1.003	22.4 ± 5.3	0.66 ± 0.07	37.9 ± 3.0	0.40 ± 0.04
		CB	6.0	0.990	12.7 ± 4.4	0.69 ± 0.11	12.5 ± 4.8	0.82 ± 0.13
		C	9.0	0.991	10.9 ± 2.2	0.94 ± 0.16	11.6 ± 1.8	0.84 ± 0.14
	2020	A1	6.0	0.987	67.2 ± 7.7	0.74 ± 0.08	45.6 ± 2.8	0.26 ± 0.03
		A2	8.0	0.994	32.2 ± 7.5	0.77 ± 0.07	32.6 ± 4.0	0.38 ± 0.04
		BC	8.0	1.005	14.8 ± 2.1	0.94 ± 0.10	16.9 ± 2.6	1.23 ± 0.03
		C	8.0	1.002	11.3 ± 1.4	0.98 ± 0.09	10.4 ± 0.9	0.83 ± 0.01

Table 3. Values of bulk density (BD), mean ± standard error of total organic carbon content (SOC), recalcitrant organic carbon content (ROC), SOC stock (SOCstock) and ROC stock (ROCstock) of the 0–30 cm interval depth of soil profiles dug from 2005 to 2020 in a 15-year-old chestnut orchard for fruit production (CO) and a chestnut coppice (CC).

Site	Year	Thickness	BD	SOC	ROC	SOCstock	ROCstock
		cm	g cm^{-3}	g kg^{-1}	g kg^{-1}	Mg ha^{-1}	Mg ha^{-1}
CO	2005	30.0	1.007	26.9 ± 1.8	0.66 ± 0.08	80.8 ± 4.9	1.97 ± 0.30
	2010	30.0	1.004	41.2 ± 9.2	0.81 ± 0.07	124.2 ± 11.7	2.44 ± 0.23
	2015	30.0	0.996	44.4 ± 7.1	0.92 ± 0.12	133.1 ± 23.3	2.76 ± 0.45
	2020	30.0	0.997	55.6 ± 7.8	1.43 ± 0.16	166.7 ± 23.5	4.25 ± 0.68
CC	2005	30.0	0.997	27.8 ± 4.5	0.72 ± 0.11	109,0 ± 11.4	2.22 ± 0.34
	2020	30.0	0.997	29.0 ± 4.7	0.87 ± 0.09	105.5 ± 10.3	2.70 ± 0.11

Taking into consideration the pedogenic horizons, while under CC, the SOCstock and ROCstock values did not change between 2005 and 2020, under CO, the stock values increased for each soil horizon with higher increasing rates for ROCstock compared to SOCstock. Specifically, from 2005 to 2020, the SOCstock increased by 172, 113, and 79% in the A, AC, and C horizons, respectively, and the ROCstock increased by 327, 196, and 89% in the A, AC, and C horizons, respectively.

4. Discussion

According to the IPCC guidelines, the methodology used for the present study can be considered eligible for the C credit market. In fact, the conversion of CC to CO took place later than 1990 and generated a co-benefit for other ecosystem functions such as food production. The additionality criterium was addressed because the CC was set as a baseline that accurately reflects the standard practices. In order to avoid biases over time, the baseline conditions have been updated through the sampling carried out in 2020. Also, the present study can be considered eligible for the C credit market because the methodology used for soil sampling and carbon quantification can be considered robust and replicable. In addition, the present study matched with the proposal for the first EU-wide voluntary framework to reliably certify high-quality carbon removals adopted by European Commission [77]. In fact, the QU.A.L.ITY criteria of quantification, additionality, long–term storage and sustainability [77] were addressed.

Further, in accordance with LULUCF [78], the change from CC to CO can be included within the "land converted to cropland" category due to the conversion of land from natural states to cropland.

The scarce soil development (i.e., lack of B-like horizons and a thinner A horizon) in CO can be attributed to clearcutting practices carried out before CO establishment. In fact, clearcutting can cause the acceleration of the soil erosion processes in mountainous areas [79], and therefore it can prevent soil development [80]. The likely higher soil erosion processes that occurred after clearcutting might explain the lower SOCstock in CO compared to CC in 2005 [81].

The roughly 5.7 Mg ha^{-1} yr^{-1} increase of organic C stock observed down to 30 cm soil depth between 2005 and 2020 in CO highlights the key role of soil on C sequestration. The SOCstock increasing rate resulted in being 3.8 Mg ha^{-1} yr^{-1} if the CC soil sampled in 2005 was considered. In both cases, such increasing rates were within the range found by previous studies conducted worldwide, both in natural and agricultural lands [82–85]. The observed soil organic C stock increase fits with the targets of the "4per1000 initiative: Soils for Food Security and Climate" in the United Nations Framework Convention for Climate Change: Conference of the Parties (UNFCCC-COP 21) in Paris. In fact, this plan of action proposed to increase on average globally 0.6 Mg of C ha^{-1} yr^{-1} to compensate for the annual CO_2-C emissions from fossil fuels [86,87]. In addition to these comforting results, in the present paper, we considered the deepest soil layers, which are recognized to have a noticeable role in organic C sequestration [88,89]. In fact, subsoil is characterized by lower amounts of available oxygen and microbial biomass and higher amounts of no–saturated soil mineral particles, which prevent organic C mineralization and promote C stabilization processes [90]. Despite this, the subsoil is considered susceptible to land use change and management [88,89,91–93], which, if not appropriate, could reduce its carbon stock. This fact would point out that the soil organic carbon storage implementation under the carbon credit initiative is feasible, assuming the entire soil profile by applying economically viable agronomic practices and good environmental practices. In our case, the conversion from CC to CO increased the organic C stock from 2005 to 2020 within both the uppermost soil horizon and the deepest ones. Because of the slower turnover of organic C of subsoil compared to that of topsoil [94], the C credit market should pay more attention to the former than to the latter. In this sense, the increase of organic C stock within the subsoil pedogenic horizons of the considered study sites would draw a picture of where chestnut orchards can be considered suitable to gain carbon credits.

Within the CO, the observed increase of SOC concerned both the labile and the most stable form (ROC). The increased amounts of both organic C forms can be considered suitable in view of soil functioning. Specifically, the labile fraction of SOC is considered a quickly reactive indicator of soil fertility and health, acting as an energy supply for soil microorganisms, a short-term reservoir of nutrients and a food source for soil fauna [95]. Therefore, keeping high labile organic C concentrations in the soil can allow for maintaining crop performance and food security. The stable organic C that can be found in both the chemically-recalcitrant and physically-protected forms [96–101] helps soil function as a long-term carbon sink. Therefore, in a wider view of soil management practices addressed to increase organic C stock, the application to soil of organic fertilizers should ensure the provisioning of labile organic C other than of the stable one to preserve the soil microbial community. However, the application of organic fertilizers with a high amount of labile organic forms could boost the mineralization of the SOC, including the stable forms [102,103].

Within the CO, most of the organic C stock increase was observed 5 years after plantation, while this rate decreased in the following years. The changing of the C storage rate pointed out the importance of taking into consideration at least 10 years as the time frame for the evaluation of C change into the soil to avoid C credit overestimation. This fact is in accordance with previous studies [104–108], which proposed 10–15 years as the time frame for soil carbon credit calculation.

However, it is important to highlight that in the considered CO, the soil surface was covered by grasses, while plant residues were left on the soil's surface and shredded. In fact, previous papers reported the important role of grasses in increasing soil organic C content because of their contribution to both organic C input and soil erosion prevention [109–111]. Similarly, plenty of literature can be found on the importance of plant residue preservation on the soil's surface for SOC accumulation [112,113].

The proposed soil sampling scheme used within the selected orchards was in accordance with that suggested by previous studies [114,115]. Specifically, in our proposed methodology, one composite soil sample was collected for an area of 2500 m^2. This sampling can be considered ideal for obtaining reliable and representative values about soil properties [114,115]. Further, the use of a relatively small sampling grid is optimal for soil properties assessment because of their high spatial variability [116–118].

Regarding the soil sampling methodology, in the present investigation, the soil samples were collected from each identified pedogenic horizon. The B horizons were not observed in CO, likely due to the intense erosion processes that occurred after clear-cutting [119,120]. Despite this, it is important to mention that combining C evaluation with the identification of pedogenic soil horizons should be recommended. It is recognized how the factors of pedogenesis influence soil processes and, in turn, the organization of soil in terms of horizon types [71]. Such an organization has economic value because the processes occurring within the horizons determine soil functionality and produce ecosystem services [121]. In this sense, human activities can negatively modify horizons' development with the consequence of soil degradation [122]. Therefore, to avoid loss of soil pedodiversity and functionality due to soil degradation processes [122,123], the forest and agricultural practices addressed to increase soil organic carbon stock must prevent the loss of the pedogenic horizons. This fact, within the soil carbon credit framework, will result in the payment of carbon credits only for those stakeholders that promote carbon accumulation, preserving the pedogenic horizons.

5. Conclusions

The present study proposes a reliable methodology helpful for improving the protocols for crediting soil carbon. The proposed methodology can be considered eligible for the C credit market. In fact, the conversion of CC to CO took place later than 1990 and generated a co-benefit for other ecosystem functions such as food production. The additionality criterium was addressed because the CC was set as a baseline that accurately reflects the standard practices. In order to avoid biases over time, the baseline conditions have been updated through the sampling carried out in 2020. Also, the present study can be considered eligible for the C credit market because the methodology used for soil sampling and carbon quantification can be considered robust and replicable.

Besides this, the proposed methodology would result in being accurate from an environmental point of view because both SOC forms and the organic C related to the pedogenetic horizons were considered. In fact, the evaluation of such properties allows us to understand the influence of treatment on soil functionality. Specifically, besides the treatment should promote soil C storage, it should preserve the other soil functions (e.g., to support soil microbial community and its activity). In addition, the proposed methodology highlighted the importance of subsoil within the C credit market mainly because the subsoil is recognized to have a noticeable role in organic C sequestration. Concerning CO, it can be considered suitable to gain carbon credits in mountainous areas. In fact, a quite rapid increase of both SOCstock and ROCstock was observed. Further, a large increase in both stocks was observed within the deeper soil horizons.

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