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Is Soil Contributing to Climate Change Mitigation during Woody Encroachment? A Case Study on the Italian Alps

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Abstract: Background and Objectives: Over the last few decades, the European mountain environment has been characterized by the progressive abandonment of agro-pastoral activities and consequent forest expansion due to secondary succession. While woody encroachment is commonly considered as a climate change mitigation measure, studies suggest a still uncertain role of the soil organic carbon (SOC) pool in contributing to climate change mitigation during this process. Therefore, the objective of the study is to investigate the possible SOC variations occurring as a consequence of the secondary succession process at the provincial level in an Alpine area in Italy. Materials and Methods: A chronosequence approach was applied to identify, in five different study areas of the Belluno province, the land use/land cover change over four different stages of natural succession, from managed grazing land to secondary forest developed on abandoned grazing land. In each chronosequence stage, soil samples were collected down to the bedrock (0–60 cm depth) to determine the changes in the SOC stock due to the woody encroachment process. Results: In all areas, small or no significant ($p < 0.05$) SOC stock changes were observed during the secondary succession in the upper 30 cm of mineral soil, while significant changes were evident in the 30–60 cm compartment, with the SOC stock significantly decreasing from 30% to 60% in the final stage of the succession. This fact indicates the great importance of considering also the subsoil when dealing with land use/land cover change dynamics. Conclusions: The recorded trend in SOC has been proved to be the opposite in other Italian regions, so our results indicate the importance of local observation and data collection to correctly evaluate the soil contribution to climate change mitigation during woody encroachment.

Keywords: climate change mitigation; common agricultural policy; rural development program; soil organic carbon; woody encroachment

1. Introduction

Natural capital, climate change, and ecosystem services availability are strictly connected to the soil quality and land-use change (LUC) dynamics around space and time [1]. To face new challenges in land degradation, most of the Multilateral Environmental Agreements indications have been translated into the United Nations Sustainable Development Goals (SDGs), addressing target definition and reframing agricultural and environmental policies at a different scale, from macro to local [2]. In that multilevel worldwide policy definitions process, the management of abandoned land could represent a crucial point for the climate change mitigation potential of agriculture and forestry activities, and particularly the role of the soil organic carbon (SOC) pool [3–5]. This issue is also recognized in the European Thematic Strategy for Soil Protection [6], and recalled in the new Green Deal European Commission proposal [7], where it was defined that the maintenance of SOC stocks is essential for the fulfilment of present and future emission reduction commitments at the European level. The 2019 Intergovernmental Panel on Climate Change (IPCC) Special Report on Climate Change and Land emphasizes that meeting the Paris Agreement's temperature goal will not be possible without radical changes in how land resources are utilized [1]. The 2030 European Union (EU) climate and energy policy framework includes a dedicated instrument concerning greenhouse gas (GHG) emissions and removals from land use; land-use change and forestry (LULUCF); and the LULUCF Regulation 2018/841 [8], where the SOC is considered as one of the five ecosystem C pools that should be reported and accounted for in managed land, especially in the case of LUC. Whether abandoned land falls in the domain of "managed land" and can thus be included in the national GHG balance depends on the local laws and regulations in each country. Nevertheless, in general, the whole territory of the EU can be considered as "managed", as it is somehow subject to human activities, policy, and measures (e.g., fire protection, land planning, protection policies, or recreation).

Although the role of the SOC is well recognized in the European context, currently there are no specific binding laws and actions for soil protection that are often integrated in different sectorial and environmental policies (e.g., Natura 2000 network; Water Framework Directive) [9]. Actually, soil protection is pursued through partial specifications in the European Common Agricultural Policy (CAP) framework, where a farmer's payment/subsidy is conditional on compliance with some standards concerning soil management (e.g., cross-compliance), land use, and management (e.g., greening) [10,11]. Besides, in the second pillar, CAP provides voluntary agro-climate-environmental schemes financed by the European Agricultural Fund for Rural Development (EAFRD) to improve soil quality, as reported in priority 4—"restoring, preserving and enhancing ecosystems related to agriculture and forestry"—identifying a specific focus areas dedicated to preventing soil erosion with the 1305/2013 EU regulation [12]. The active management of these marginal territories could be considered a strategy for both climate change mitigation and soil protection in marginal mountain areas.

Land abandonment and the consequent woody encroachment is an extensive phenomenon in European mountain territories and, particularly, in the Mediterranean area [13–15]. The woody encroachment process occurring in marginal lands causes a natural LUC, which is responsible for a shift in land cover, causing profound changes in the structure of the ecosystem and in the fluxes of C connected with the different ecosystem C pools [16]. Apart from an obvious increase in the C stored in the biomass (both aboveground and belowground) as a result of the change in vegetation, the woody encroachment process may have a dissimilar impact on the SOC pool as a function of the considered LUC [17,18], with clear and significant SOC stock increment when occurring on cropland, and highly variable effects over managed or unmanaged grasslands [17–21]. In the case of grasslands, the main reason for this variability can be related to several parameters and their combination. A significant role in driving the direction of the SOC stock changes along the woody encroachment process is played by the forest types (conifers vs. broadleaves) [17,19] and the site's climatic conditions, mainly mean annual precipitations and mean annual temperatures [17–21]. As woody encroachment begins, lands undergo profound changes in species composition, patch-type diversity, and microclimate [19,22]. Besides, the shift toward forest can change the soil fauna composition in favor of species less capable of transferring the C inputs (e.g., litter deposition) into the mineral soil [23,24], particularly in conifer-dominated secondary forests. In the most dramatic situations, these changes can cause a SOC depletion, which is usually overturned by the C accumulated in the organic layer [25,26] and aboveground biomass [27].

Although some studies do not clearly indicate soil as a major C reservoir contributing to climate change mitigation trough SOC sequestration along this natural land use change [17,18,20,22,26], some others suggest a major role of the soil compartment [3–5,19,28]. This fact indicates the importance of understanding the role of the soil to act as a C sink or source with respect to the woody encroachment process to correctly define future politics aimed at increasing C sequestration by terrestrial ecosystems. The LULUCF regulation poses also a new challenge to EU Member States that will need to report, starting from 2023, on the basis of a spatial explicit approach that implies that the land parcels where LUC occurs need to be identified and the GHG emissions and removals tracked, thus giving the opportunity to characterize the GHG fluxes with local specific factors.

Based on these premises, the aim of this study was to quantify the SOC changes due to the natural succession toward forest occurring on abandoned grazing land in the Italian Alps, in the Belluno province. This aim is justified by the increasing European area affected by land abandonment and the possible contribution to climate mitigation offered by the SOC pool in connection with the orientation of agricultural land management policies in mountain rural areas under the Common Agricultural Policy.

2. Materials and Methods

2.1. Study Area

The study sites are located in the Belluno province, Veneto Region, Italy (Figure 1a,b). The climate of the province is typical of the Alpine regions, with a mean annual temperature of 10 °C and a mean annual precipitation of about 1200 mm (www.arpa.veneto.it), which varies in the different areas of the province according to altitude and location (Table 1). The province entirely coincides with part of the Piave river basin. The territory constitutes 81% agricultural and forestry areas. The province is a typical Alpine province, with scarce arable lands and an abundance of permanent grazing lands, meadows, shrublands, and forests. The main soil types are comprised within the order of Cambisols and Phaeozems [29], and are usually shallow on the mountain slopes and moderately deep in the valley bottom [30].

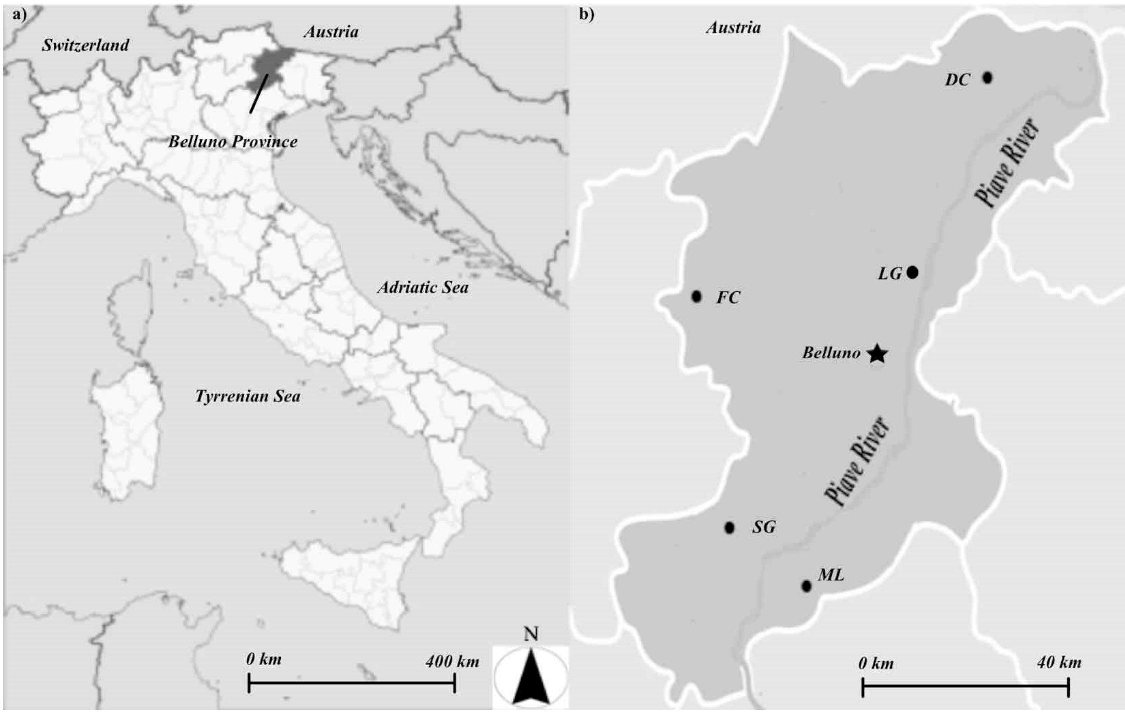

Figure 1. (**a**) Location of the Belluno province within Italy, and (**b**) the five sites distributed over the Belluno province. DC = Danta di Cadore; FC = Falcade; LG = Longarone; ML = Mel; SG = Santa Giustina.

Table 1. Main features of the five sites where the chronosequences were located. DC = Danta di Cadore; FC = Falcade; LG = Longarone; ML = Mel; SG = Santa Giustina.

Site	Elevation	MAT ∞	MAP §	Latitude †	Longitude †	Exposition Ω	Slope	Soil Type *
	m a.s.l.	°C	mm	N	E		%	
DC	1483	3.5	1043	46.5683	12.5122	SE	16	Cambisol
FC	1289	1.5	1228	46.3577	11.8736	S	40	Phaeozem
LG	1278	6.1	1337	46.2724	12.3006	SE	15	Phaeozem
ML	1288	6.5	1521	46.0618	12.0789	NW	10	Phaeozem
SG	1224	8.3	1559	46.0864	12.0442	SE	50	Phaeozem

∞ Mean annual temperature; § mean annual precipitation; † WGS 84 decimal degree; Ω SE = South–East; S = South; NW = North–West; * [29].

2.2. Experimental Design

To evaluate the changes in SOC caused by woody encroachment, we used a chronosequence approach which corresponds to the so-called space-for-time substitution suggested by Walker et al. [31]. Therefore, we identified, in a close range, a set of spatially separated areas, similar for exposure, slope, and elevation, but different for recent land use and land cover history, which represent stages encroached in different periods over time. These areas were subjected to a synchronic analysis in the field. We identified five chronosequences (hereafter called sites) from different municipalities of the Belluno province: Danta di Cadore (DC), Falcade (FC), Longarone (LG), Mel (ML), and Santa Giustina (SG) (Figure 1b). In each site, we selected a pasture currently managed to represent the starting point of natural succession (T0). In order to define the land use patterns over time, all the T0s were identified using the beneficiary lists of the Rural Development Programme (RDP) measure for the maintenance of grasslands (measure 214/e) of the Veneto RDP funds [32], which concerned all sites since 2013. By combining the use of airborne digital orthophoto series from 1988 to 2009, interviews with local farmers, and the beneficiary list of the RDP measure for the restoration of grasslands affected by woody encroachment (measure 216-6) of the Veneto RDP [32], it was possible to individuate three more stages of the succession: (1) abandoned grazing land at the initial stage of the succession, with herbaceous vegetation and shrubs (T1); (2) abandoned grazing land at an intermediate stage, with abundant woody vegetation and shrubs (T2); and (3) abandoned pasture at an advanced stage of the succession, with the forest canopy closed (T3). In summary, 5 sites with 4 stages each were individuated. On the basis of the previous data sources and combining areal images with interviews with local farmers, we were able to assign an approximate abandon age to each of the stages: 15 years for T1, 35 years for T2, and around 70 years for T3 (A1–A5). The vegetation species of each stage from the different chronosequences along with the information on the age of the stage and the size of the area covered by the stage are reported in Tables A1–A5. In each site, the chosen stages were located close to each other, with 500 m being the maximum distance.

2.3. Sampling Strategy and Soil Analyses

The protocol proposed by the European Commission [33] to determine SOC variations as a consequence of a land-use change was selected for the soil sample collection. The protocol is based on a pseudorandom selection of three plots in each successional stage. Following the protocol, the dimensions of the plots were determined according to the dimension of the area covered by each successional stage [33]. In addition to the recommendation suggested for this protocol application [34], in this study we made an implementation considering the whole soil profile to the bedrock and not only the 0–30 cm layer. In particular, the sampling was performed in the topsoil at 0–5, 5–15, and 15–30 cm depths and in the subsoil at 30–45 and 45–60 cm depths. In each of the plots, soil samples were collected by means of an auger in 25 points distributed on the basis of a 5 by 5 sampling grid according to the ISO 10381-4 standard [35]. The 25 samples collected per plot and layer were mixed in the field to have one composite sample to be used for the analyses. Considering the three plots, there were three composite samples per depth in each chronosequence successional stage. In the center of each plot, a trench was opened to a 40 cm depth and used to collect bulk density (BD) samples using a known volume (98.1 cm^3) metal cylinder according to Blake [36] for the depths comprised in the topsoil. When present, the organic horizon was collected within a frame of 40 by 40 cm randomly positioned in each plot to obtain three replicates per stage. In summary, 5 sites with 4 stages each were sampled. In each stage, 3 sampling plots were considered and, for each of them, a composite sample (based on 25 subsamples) was collected for each layer (5 depth intervals). Overall, 480 soil samples were collected (300 for soil and 180 for BD).

All the samples were oven-dried (60 °C) to a constant mass. The organic horizon was ground in a ball mill, while the mineral soil was sieved at 2 mm and the chemical analyses were performed on the fine earth fraction (<2 mm). The particle size distribution was determined by the pipette method, while the pH was measured in a 1:2.5 soil/water suspension using a pH meter electrode [37]. The total C was measured on finely ground samples by dry combustion (Thermo-Finnigan Flash EA112 CHN, Okehampton, UK). The SOC stock (in kg C m^2) of the *i* soil layer was calculated for each depth according to Poeplau et al. [38] and Hobley et al. [39]:

$$\mathrm{SOCstock_i} = \mathrm{SOCconc_{fine\ soil}} * \mathrm{BD_{sample}} * \mathrm{depth_i} * (1 - \mathrm{Rock_{mass}}),$$

where $\mathrm{SOCconc_{fine\ soil}}$ is the organic C concentration of the fine earth (g C kg^{-1} soil), $\mathrm{BD_{sample}}$ is the apparent soil bulk density (g soil cm^{-3}), $\mathrm{depth_i}$ is the depth of investigated (*i*) soil layer (cm), and the $\mathrm{Rock_{mass}}$ is the rock fragments fraction in mass percentage (mass%/100). The SOC stock estimates were, then, converted into Mg C ha^{-1}. For the two layers comprised in the subsoil compartment, the BD was estimated using the pedotransfer function proposed by Adams [40]:

$$BD = \frac{1}{(a + b * \%C)},$$

where *a* and *b* are two constant values (0.686 and 0.085, respectively) suggested by Chiti et al. [41] for deep soil layers, and %C is the SOC percentage. In line with the IPCC guidelines [42], the changes in the SOC stock were reported for the topsoil (0–30 cm) and, to have an indication of the contribution from the subsoil, the changes were reported also down to the bedrock (30–60 cm).

2.4. Statistics

The C concentration and C stock of the different soil layers were tested for normality and homoscedasticity using Anderson–Darling and Levene's tests [43], respectively. The differences in the means of the C concentration and C stock between stages were tested for significance using a one-way analysis of variance (ANOVA) between different stages, incorporating repeated measures. A post-hoc Tukey's test at $p < 0.05$ was used, whenever necessary, to reveal significant differences among the mean values. The entire statistic was implemented using the R software [44].

3. Results

3.1. Soil Physical and Chemical Parameters

The similarity of the main physical (i.e., particle size distribution) and chemical parameters (i.e., pH) between the stages of each chronosequence assured site comparability, while some differences were observed between different areas (Tables A6 and A7). In the different areas, the particle size distribution varied from loam (DC, SG) to clay-loam (FC, LG) and silty clay-loam (ML). Concerning the pH, no significant variations were observed between the same layer in the different stages of each chronosequence. The bulk density increases with depth within a stage, but non-significant differences were observed from the T0 to the T3 stages within the same area (Table A8). In terms of rock fragments, we observed a general higher content in mature forest (T3) stages than in the corresponding grazing lands, possibly explained by the fact that those sites were the first to be abandoned, the presence of stones being higher and the sites being basically less productive (Table A8). In terms of SOC concentration, within each stage there is a gradual decrease with depth. The comparison of the same stage from different sites reveals significant differences, particularly in the 0–5 cm layer, with grazing land (T0) showing values ranging from 61.3 ± 5.0 (DC) to 113.6 ± 9.7 g C kg^{-1} (LG). The same variability is evident for the T3 stage, with values ranging from 71.7 ± 2.5 (SG) to 117.3 ± 8.8 g C kg^{-1} (LG) (Figure 2; Table A9). The lowest SOC concentration values in all the layers are always in the DC and SG sites, with the Cambisol and Phaeozem soil types, respectively. ML is the only site where the SOC concentration does not show any statistical differences among the stages in each layer. In the other sites, significant changes in SOC concentration occur without any apparent common trend in the topsoil layers, while in the subsoil layers (30–45 and 45–60 cm) the T0 stages are always characterized by higher SOC concentrations (generally between 10% and 60%) than those of the T3 ones (Figure 2; Table A9).

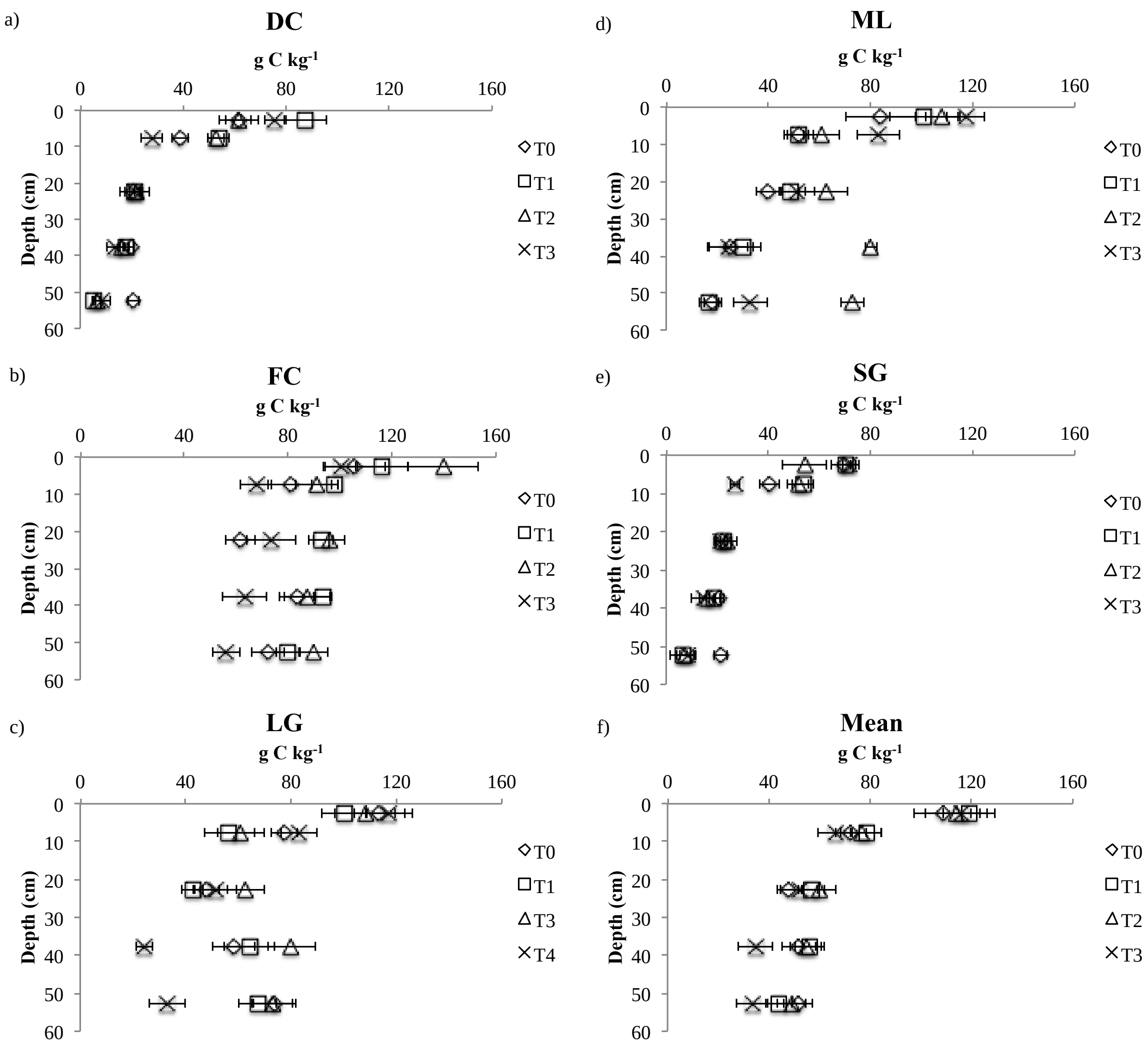

Figure 2. Soil organic carbon (SOC) concentration (g C kg^{-1}) in the different soil layers of the different stages along the natural succession. Symbols represent mean values, and uncertainty bars correspond to standard deviations (n = 3). Each panel (**a**–**e**) refers to a specific site (DC = Danta di Cadore; FC = Falcade; LG = Longarone; ML = Mel; SG = Santa Giustina). Panel (**f**) includes the mean and standard deviation estimations for Belluno province (n = 15).

3.2. SOC Stocks Changes

Considering the topsoil (0–30 cm interval), no significant changes in SOC stock occur over time, from T0 to T3, in the LG, FC, and ML sites. In DC, a significant increase was observed in the T2 intermediate stage, while in SG a significantly lower SOC stock was estimated in the T2 and T3 stages, with a SOC stock loss of more than 50% of that estimated for T0 (Figure 3 and Table A10).

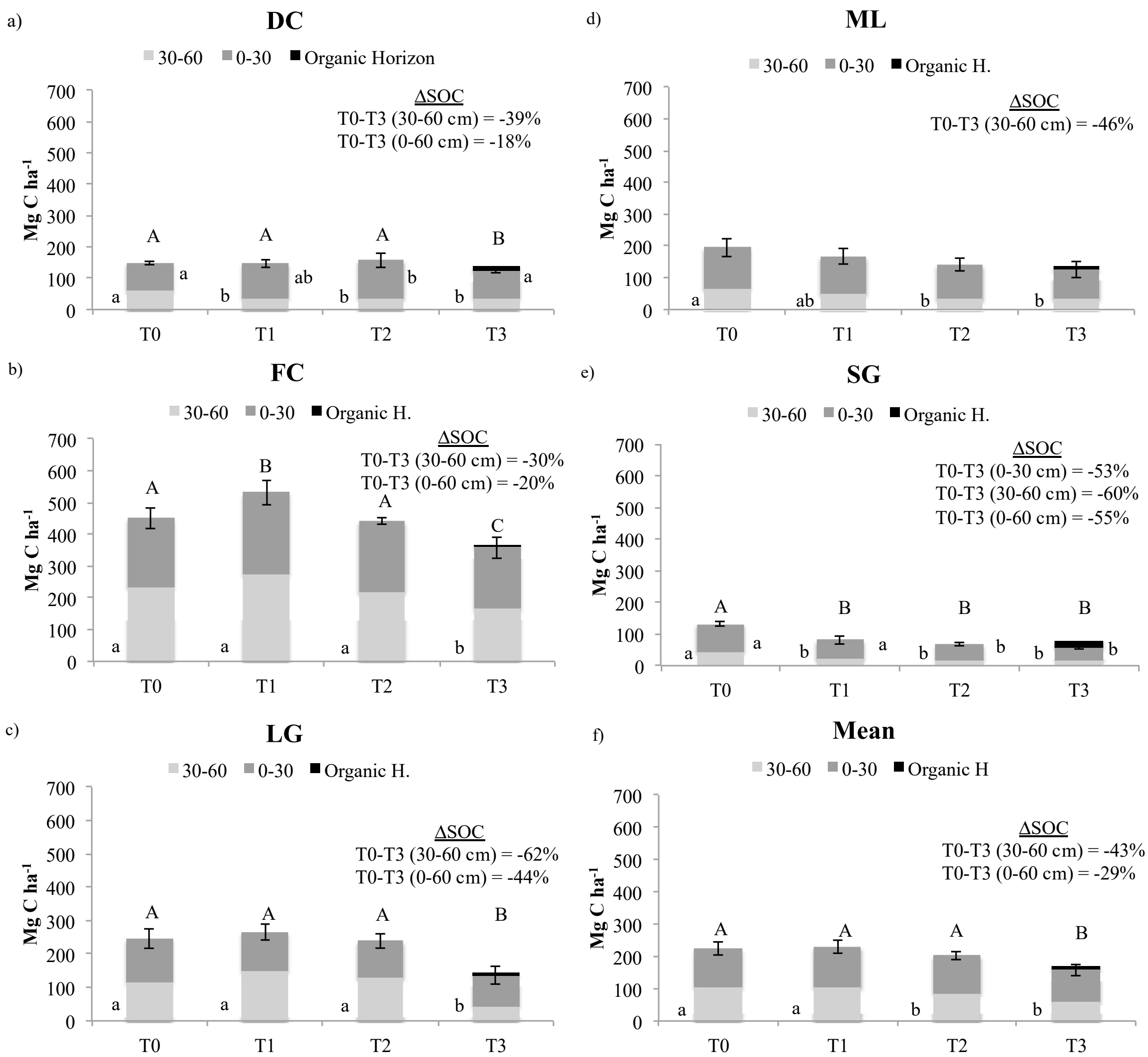

Figure 3. Mean and standard deviations (n = 3) for SOC stock in the mineral soil (0–60 cm), topsoil (0–30 cm), and subsoil (30–60 cm) compartments. Organic horizon is reported only in the T3 stage, because in the other stages it was not present. Each panel (**a**–**e**) refers to a specific site (DC = Danta di Cadore; FC = Falcade; LG = Longarone; ML = Mel; SG = Santa Giustina). Panel (**f**) includes the mean and standard deviation estimations for Belluno province (n = 15). Capital letters indicate significant differences (Tukey; $p < 0.05$) among stages; lower case letters indicate statistical differences among stages in the topsoil (letters on the right side of the bars) and in the subsoil (letters on the left side of the bars). No letters indicate no significant difference. ΔSOC are reported only when significant differences were present for the specific soil compartment.

Most of the changes were observed in the subsoil (30–60 cm layer), with the SOC stock significant decreasing from the T0 to the T3 stage in all the sites. The T3 stage shows on average an SOC stock 39% (DC), 30% (FC), 62% (LG), 46% (ML), and 60% (SG) lower than the T0 stage (Figure 3).

Taking into consideration the whole soil profile (0–60 cm), except in the ML site where no significant SOC changes were estimated, the loss of SOC in the final T3 stage ranges from 10% in DC to 55% in SG. Considering the mean SOC stock from all sites (Figure 3f), in the 0–30 cm layer the SOC stock significantly decreases only in the T3 stage, while in the 30–60 cm layer the decrease is significant already in the T2 stage. Considering the whole profile, the trend is identical to that of the topsoil.

The organic horizon, which is present only in the final forest stage, shows a C stock ranging from 7.0 ± 1.4 (FC) to 20.7 ± 6.3 Mg C ha^{-1} (SG) (Figure 3, Table A10).

4. Discussion

4.1. Impact of Land Abandonment on the SOC Pool

Temperatures [19,20] and precipitations [18,21,45] are thought to be the main determinants for the SOC changes occurring after land abandonment and woody plant invasion on grazing lands. The estimated SOC stock changes between managed grasslands (T0 stage) and encroached forest stages (T3) do not show any statistical correlation, nor mean annual temperature, nor mean annual precipitation (data not shown). However, the small range of values, especially for the precipitation parameter (1224–1483 mm yr^{-1}), can justify the absence of these correlations.

According to an Italian study by Alberti et al. [45], 900 mm of mean annual precipitation represents the threshold for SOC changes, with the SOC levels decreasing in areas of high precipitation (>900 mm yr^{-1}) and increasing in areas with low precipitation. Our results for the Belluno province, with an average precipitation of about 1200 mm, are in line with the literature, showing that grazing land abandonment generally leads to a SOC stock decrease. However, this decrement is evident only considering the whole profile (0–60 cm) rather than considering the topsoil (0–30 cm), where no changes were observed. This fact indicates the great importance of considering also the subsoil when dealing with LUC dynamics, as was observed also by Poeplau et al. [20] for temperate zones and by Pellis et al. [19] in different mountain areas of Italy. This is mainly explained by the fact that the C vertical distribution along the profile depends not only on the soil characteristics (e.g., pedological class, texture) but also on the climate parameters [21] and vegetation types [19]. Forest canopy closure may alter the microclimatic conditions, reducing the summer temperature in comparison to open grasslands, thus reducing the organic matter decomposition rate [46]. This fact implies, as observed, in the forest stages, an aboveground litter accumulation in the organic layer, which is very small or not present in grazing land. In addition, conifers, which dominate the investigated forest stages, can produce a more recalcitrant and slowly decomposable litter compared to herbaceous vegetation [47,48]. Besides, conifer forests are generally characterized by a reduced presence of grasses and understory vegetation, which produce highly palatable dead organic matter [49]. These conditions generally reduce soil pH with respect to grazing land and inhibit heartworm activity and their vertical organic matter translocation [24,50]. In this study, the pH (Tables A6 and A7) does not show any significant variation in soil acidity, probably because the forest stages are not old enough to significantly affect this parameter. Finally, Puhe [51] noticed that conifer fine roots, which are affected by a rapid turnover, are mainly limited to the upper 10 cm of depth. Therefore, the main (above- and below-ground) litter deposition in the upper soil part, with the alteration of the microclimate conditions, supports our results of an SOC stock reduction in the subsoil compartment during the woody encroachments process.

Organic horizons are present only in the mature forest stages (T3), and the C stored in this compartment is not enough to offset the sizable, even if not always significant, mineral soil C losses. Similar to this study, Thuille et al. [52], Thuille and Schulze [26], Alberti et al. [17], and Guidi et al. [22] observed a SOC decrease from the mineral layers due to forest expansion in abandoned grazing lands on the Italian Alps, despite some studies that also reported no changes or even an increase in the SOC stocks in montane areas of Spain [53], Switzerland [27], and Italy [19]. In this regard, the trend in SOC emission/reduction can vary greatly depending on the pedo-climatic conditions, but currently no site-specific data collection programs are present to characterize the different pedo-climatic situations [54].

Looking at the C stored at an ecosystem level allows for a better understanding of the mitigation potential due to woody encroachment into abandoned grazing lands. A study performed in one of the sites considered in this study (the ML site) by Pellis et al. [19] indicates that the C stock in the aboveground biomass of grazing land (T0) was 0.2 Mg C ha^{-1}, while the belowground C pool was about 13 Mg C ha^{-1}. On the contrary, in mature forests (T3) the aboveground biomass was 156 Mg C ha^{-1} and the belowground C pool was about 30 Mg C ha^{-1}. Besides, the C in the organic horizon pool, ~10 Mg C ha^{-1}, and that in the deadwood C pool, ~3 Mg C ha^{-1}, need to be considered also [19]. Hence, looking at the process of woody encroachment at an ecosystem level, it is evident that the C sink effect of the growing living biomass (above and below ground) and the deadwood and organic horizon C accumulation overturn the C losses observed for the soil compartment. On the basis of the previous data, we suppose that, in the investigated area, the woody encroachment can have a mitigation potential ranging from 70 (LG) to 160 Mg C ha^{-1} (ML and DC). In other montane areas of Italy (e.g., along the central and southern Apennines), the mitigation potential is much higher, ~300 Mg C ha^{-1} [18,26], mainly due to the increase in SOC, with about 45% more SOC in forestland (T3) than in grazing land (T0). Considering climate change mitigation, in the long term a forest ecosystem can accumulate a greater amount of C than grazing lands and transitional phases. The main concern is the time needed by the natural succession to be completed—at least 70–100 years [19,28] in the Italian territory or longer, even more than 150 years, in temperate forests [20]. Besides, during the succession most of the C is stored in tree biomass and organic layers, which constitute less stable C pools due to external disturbances (e.g., management, harvesting, and environmental modifications), compared with the C stored in the mineral soil layer.

4.2. Implication for Rural Development Programmes and Climate Policies

The abandonment of agricultural activity and natural reforestation phenomena are very diffuse in most of the Alpine territories [55]. The Rural Development Programmes (RDPs) are the main tools for the allocation of the European Agricultural Funds for Rural Development, where the preservation of soil against erosion and the improvement of soil management are identified as key priorities (priority 4). Many RDPs identify that the loss of grazing lands, located on shallow soil on steep slopes, can lead to an increase in hydrogeological risk and erosion, in addition to the serious compromise of historic rural landscapes and, lastly, the loss of biodiversity that characterizes mountain open spaces [56,57]. In Italy, regional administrations are in charge of designing the RDP, and within the Veneto Region RDP objectives, the Alpine landscape and environment are identified as focus area for intervention. Coherently with the general trend over the Alps, the forest area in the Belluno province increased up to 20% and agricultural lands decreased by 40% from 1980 to 2000 [58]. To enhance agroforestry practice adoption and to safeguard alpine biodiversity habitat, in 2013 the Belluno province financed 87 projects devoted to mountain grazing land restoration measures under the RDP (measure 216-6) and involving about 600 hectares of interventions [59]. In the current RDP programming for the period 2013–2020, similar landscape restoration actions are promoted [60]. The implementation of such measures implies that, for the Veneto Region, over 1000 ha are currently affected by the woody encroachment process.

The climate change mitigation potential is only one of the different ecosystem services provided by grazing lands; nevertheless, its quantification can be helpful for co-defining different policies using a multiple-criteria decision analysis approach [61]. The results from this study could be used by the Veneto Region to better assess the effect of grazing land restoration measures considering the focus area "e" objectives (fostering C conservation and sequestration in agriculture and forestry).

Besides, at the European level the LULUCF sector is increasingly playing a key role also in the climate policy framework. The decision of the European Commission, n. 529/2013/EU [62], required Member States to report the emissions and removals of GHG resulting from LULUCF activities, though not contributing to the EU 2020 objectives. With the recently approved LULUCF regulation for the post-2020 period [8], the sector's emissions and removals are allowed to contribute towards the EU 2030 policy framework target, although with some limitations [63]. Both systems (current decision and future regulation) make mandatory, among other things, the accounting and reporting of emissions and removals in grazing land, cropland, and managed forests, as well as emissions and removals due to conversions from and to forestland. Data from the European National Inventory Report show that the LULUCF sector is responsible for a net sink of –255 810 GgCO_2eq (69 766 GgC) in 2018 (EU27 +

Iceland and UK), with an increasing trend from 1990 mainly due to the natural expansion of grazing land and forestland [64]. Similarly, in Italy the sink in the LULUCF sector is increasing at an average of about 237 GgC per year [65]. Between 1998 and 2017, the conversion of 1.3 million ha from grazing land to forestland led to a sink of 1161 Gg C yr^{-1}, of which 238 Gg C yr^{-1} is attributed to the SOC pool (data related to 2017). Nevertheless, in the National GHG Inventory, the estimation of SOC due to conversion from grazing land to forestland is based on a single grazing land default value of SOC for the whole Italian territory ($SOC_{0\text{–}30\ cm}$ = ~79 Mg C ha^{-1}), while for forest soils six values for the 0–30 cm depth are used for different time periods, ranging from ~80 to 82 Mg C ha^{-1}, thus always implying an increase in the C content in land that is converted from grazing land to forest. The coarse representation of the SOC changes is due to a lack of specific studies and a lack of detailed information about the location where the LUC occurs, which is a common gap in the EU inventories. In the post-2020 period, the new LULUCF regulation will require Member States to report flux data using a geographically explicit approach, thus allowing the use of local specific data to refine their National Inventory Reports.

5. Conclusions

Conversion to forestland is commonly considered as a climate change mitigation measure, and afforestation is included in many nationally determined contributions under the Paris Agreement (see China, India, Honduras, Senegal, etc.). On the other hand, its potential highly depends on the type of land use where forest is established and local environmental conditions, especially the precipitation rate. In some cold temperate conditions of the Alps, such as the area considered in this study, forest encroachment on grazing land has a reduced potential to sequester C at an ecosystem level, mainly due to the contribution of the mineral soil compartment, where there is an evident loss of SOC when considering the whole profile. This study highlights the importance of local observation and data collection to improve trade-off evaluation among ecosystem services connected to agro-silvo-pastoral practices in mountain areas.

In conclusion, these results add a precise quantification of the SOC changes, providing information useful for greenhouse gases inventories and to drive decision makers to co-define policies for a multiple-criteria decision analysis approach at the regional level.

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Appendix A

Table A1. Main vegetation species present in the different successional stages, along with their age, the size of the area covered by the specific stage, and the size of the plots at Danta di Cadore (DC).

Area	T0			T1			T2			T3		
	Vegetation *	Age	Area m^2	Vegetation *	Age	Area m^2	Vegetation *	Age	Area m^2	Vegetation *	Age	Area m^2
DC	H = Arrhenatherum elatius (L.) P.Beauv. ex J.Presl & C.Presl., Dactylis glomerata L.	0	Stage 4976 plot ~150	H = Arrhenatherum elatius (L.) P.Beauv. ex J.Presl & C.Presl., Dactylis glomerata L.; S = Sorbus aria (L.) Crantz, Juniperus communis L.	~15	Stage 29,830 plot ~625	H = Dactylis glomerata L.; S = Sorbus aria (L.) Crantz, Juniperus communis L.; T = Picea abies (L.) H.Karst., Larix decidua Mill.	~35	Stage 5203 plot ~70	S = Juniperus communis L.; T = Picea abies (L.) H.Karst., Fagus sylvatica L.	~70	Stage 5053 Plot ~200

* H = herbaceous vegetation; S = shrubs; T = trees.

Table A2. Main vegetation species present in the different successional stages, along with their age, the size of the area covered by the specific stage, and the size of the plots at Falcade (FC).

Area	T0			T1			T2			T3		
	Vegetation *	**Age**	**Area m^2**	**Vegetation ***	**Age**	**Area m^2**	**Vegetation ***	**Age**	**Area m^2**	**Vegetation ***	**Age**	**Area m^2**
FC	H = Arrhenatherum elatius (L.) P.Beauv. ex J.Presl & C.Presl., Dactylis glomerata L.	0	Stage 5390 Plot ~70	H = Arrhenatherum elatius (L.) P.Beauv. ex J.Presl & C.Presl., Nardus stricta L., Arctium lappa L.; S = Rhododendron ferrugineum L., Vaccinium spp.	~15	Stage 4669 Plot ~100	H = Nardus stricta L.; S = Juniperus communis L.; T = Corylus avellana L.	~35	Stage 4231 plot ~140	S = Juniperus communis L.; T = Picea abies (L.) H.Karst., Fagus sylvatica L.	~70	Stage 5192 Plot ~85

* H = herbaceous vegetation; S = shrubs; T = trees.

Table A3. Main vegetation species present in the different successional stages, along with their age, the size of the area covered by the specific stage, and the size of the plots at Longarone (LG).

Area	T0			T1			T2			T3		
	Vegetation *	**Age**	**Area m^2**	**Vegetation ***	**Age**	**Area m^2**	**Vegetation ***	**Age**	**Area m^2**	**Vegetation ***	**Age**	**Area m^2**
LG	H = Arrhenatherum elatius (L.) P.Beauv. ex J.Presl & C.Presl., Dactylis glomerata L.	0	Stage 233,046 Plot ~2500	H = Arrhenatherum elatius (L.) P.Beauv. ex J.Presl & C.Presl., Nardus stricta L., Arctium lappa L.; S = Vaccinium spp.	~15	Stage 16,986 Plot ~570	H = Nardus stricta L.; S = Vaccinium spp.; T = Picea abies (L.) H.Karst., Fagus sylvatica L.	~35	Stage 5748 Plot ~55	S = Vaccinium myrtillus L.; T = Picea abies (L.) H.Karst.	~70	Stage 22,749 Plot ~625

* H = herbaceous vegetation; S = shrubs; T = trees.

Table A4. Main vegetation species present in the different successional stages, along with their age, the size of the area covered by the specific stage, and the size of the plots at Mel (ML).

Successional Stages												
Area	T0			T1			T2			T3		
	Vegetation *	Age	Area m²	Vegetation *	Age	Area m²	Vegetation *	Age	Area m²	Vegetation *	Age	Area m²
ML	H = Cynosurus cristatus L., Scorzoneroides autumnalis (L.) Moench, Lolium perenne L.	0	Stage 33,273 Plot 1110	H = Cynosurus cristatus L., Scorzoneroides autumnalis (L.) Moench, Lolium perenne L.; S = Rhododendron ferrugineum L., Vaccinium spp.	5	Stage 33220 Plot 860	T = Picea abies (L.) H.Karst.	~35	Stage 10,400 Plot ~260	S = Vaccinum myrtillus L.-T = Picea abies (L.) H.Karst	>62	Stage 47,122 Plot ~340

* H = herbaceous vegetation; S = shrubs; T = trees.

Table A5. Main vegetation species present in the different successional stages, along with their age, the size of the area covered by the specific stage, and the size of the plots at Santa Giustina (SG).

Successional Stages												
Area	T0			T1			T2			T3		
	Vegetation *	Age	Area m²	Vegetation *	Age	Area m²	Vegetation *	Age	Area m²	Vegetation *	Age	Area m²
SG	H = Festuca alpestris Roem. & Schult., Festuca varia Haenke	0	Stage ~5000 Plot ~150	H = Festuca alpestris Roem. & Schult., Festuca varia Haenke; S = Rosa canina L., Sorbus spp., Juniperus communis L.	~15	Stage 45,018 Plot ~860	H = Festuca alpestris Roem. & Schult., Festuca varia Haenke; S = Sorbus spp., Juniperus communis L.; T = Picea abies (L.) H.Karst., Larix decidua Mill.	~35	Stage 15,035 plot ~280	S = Sorbus spp., Juniperus communis L.; T = Picea abies (L.) H.Karst., Larix decidua Mill.	~70	Stage 10,006 Plot ~210

* H = herbaceous vegetation; S = shrubs; T = trees.

Table A6. Particle size distribution and pH in the different successional stages at Danta di Cadore (DC) and Falcade (FC). Values represent the mean ± standard deviation (n = 3).

		Successionale Stages															
		T0				**T1**				**T2**				**T3**			
Area	**Depth**	**Sa**	**Si**	**Cl**	**pH**	**Sa**	**Si**	**Cl**	**pH**	**Sa**	**Si**	**Cl**	**pH**	**Sa**	**Si**	**Cl**	**pH**
	cm	**g kg^{-1}**	**g kg^{-1}**	**g kg^{-1}**		**g kg^{-1}**	**g kg^{-1}**	**g kg^{-1}**		**g kg^{-1}**	**g kg^{-1}**	**g kg^{-1}**		**g kg^{-1}**	**g kg^{-1}**	**g kg^{-1}**	
DC	0–5	490 ± 24	315 ± 31	195 ± 23	5.8 ± 0.2	475 ± 27	301 ± 25	224 ± 27	6.2 ± 0.2	399 ± 29	270 ± 32	331 ± 31	6.3 ± 0.2	441 ± 27	240 ± 28	319 ± 31	5.9 ± 0.2
	5–15	470 ± 21	330 ± 28	200 ± 29	6.0 ± 0.2	474 ± 29	321 ± 32	205 ± 23	6.2 ± 0.3	403 ± 27	245 ± 27	352 ± 27	6.5 ± 0.3	436 ± 32	251 ± 19	313 ± 33	5.8 ± 0.3
	15–30	486 ± 18	315 ± 29	199 ± 31	6.1 ± 0.1	489 ± 31	305 ± 29	206 ± 33	6.4 ± 0.3	412 ± 19	256 ± 32	332 ± 29	6.7 ± 0.3	423 ±25	239 ± 24	338 ± 24	6.1 ± 0.2
	30–45	490 ± 26	290 ± 23	220 ± 35	6.4 ± 0.2	490 ± 30	281 ± 25	229 ± 31	6.7 ± 0.3	424 ± 28	244 ±35	332 ± 32	6.7 ± 0.3	429 ± 28	241 ± 32	330 ± 29	6.4 ± 0.2
	45–60	495 ± 28	298 ± 26	207 ± 27	6.4 ± 0.1	465 ± 28	288 ± 23	247 ± 21	6.9 ± 0.3	413 ± 29	251 ± 28	336 ± 24	7.0 ± 0.3	410 ± 23	263 ± 31	327 ± 25	6.5 ± 0.3
FC	0–5	356 ± 33	375 ± 32	269 ± 33	6.1 ± 0.1	389 ± 32	301 ± 27	310 ± 32	6.5 ± 0.2	387 ± 22	298 ± 19	315 ± 28	5.5 ± 0.2	406 ± 19	298 ± 21	296 ± 23	6.7 ± 0.3
	5–15	338 ± 27	345 ± 28	317 ± 25	6.3 ± 0.2	378 ± 23	311 ± 22	311 ± 35	6.3 ± 0.3	393 ± 22	302 ± 27	305 ± 23	5.7 ± 0.2	416 ± 23	267 ± 25	317 ± 21	6.5 ± 0.3
	15–30	346 ± 26	361 ± 28	293 ± 23	6.4 ± 0.2	381 ± 28	319 ± 27	300 ± 31	6.7 ± 0.3	401 ± 22	296 ± 29	303 ± 29	5.9 ± 0.2	401 ± 27	303 ± 27	296 ± 19	6.7 ± 0.3
	30–45	332 ± 27	342 ± 24	326 ± 19	6.4 ± 0.2	390 ±25	321 ± 19	289 ± 29	6.7 ± 0.3	384 ± 23	279 ± 31	337 ± 31	6.3 ± 0.3	369 ± 29	297 ± 19	334 ± 29	7.0 ± 0.2
	45–60	374 ± 31	299 ± 29	327 ± 30	6.7 ± 0.2	415 ±32	297 ± 28	288 ± 27	6.9 ± 0.3	389 ±21	258± 26	353 ± 27	7.0 ± 0.3	379 ± 23	287 ± 31	334 ± 27	7.1 ± 0.2

Table A7. Particle size distribution and pH in the different successional stages at Longarone (LG), Mel (ML), and Santa Giustina (SG). Values represent the mean ± standard deviation (n = 3).

		Successionale Stages															
		T0				**T1**				**T2**				**T3**			
Area	**Depth**	**Sa**	**Si**	**Cl**	**pH**	**Sa**	**Si**	**Cl**	**pH**	**Sa**	**Si**	**Cl**	**pH**	**Sa**	**Si**	**Cl**	**pH**
	cm	**g kg^{-1}**	**g kg^{-1}**	**g kg^{-1}**		**g kg^{-1}**	**g kg^{-1}**	**g kg^{-1}**		**g kg^{-1}**	**g kg^{-1}**	**g kg^{-1}**		**g kg^{-1}**	**g kg^{-1}**	**g kg^{-1}**	
LG	0–5	369 ± 32	303 ± 35	328 ± 33	5.4 ± 0.2	401 ± 24	299 ± 22	300 ± 33	5.1 ± 0.2	356 ± 23	286 ± 32	358 ± 22	4.9 ± 0.3	403 ± 33	303 ± 21	294 ± 21	5.0 ± 0.3
	5–15	374 ± 22	298 ± 32	328 ± 36	5.3 ± 0.2	415 ± 21	301 ± 26	284 ± 31	5.7 ± 0.3	385 ± 29	265± 33	350 ± 28	5.5 ± 0.2	399 ± 32	287 ± 27	314 ± 19	5.3 ± 0.2
	15–30	367 ± 29	275 ± 35	358 ± 29	5.9 ± 0.1	403 ± 28	297 ± 29	300 ± 19	5.5 ± 0.3	398 ± 21	257 ± 29	345 ± 33	5.5 ± 0.3	388 ± 36	275 ± 26	337 ± 29	5.5 ± 0.3
	30–45	371 ± 33	261 ± 33	368 ± 29	6.3 ±0.2	398 ± 26	277 ± 33	325 ± 25	6.3 ± 0.3	401 ± 19	243 ± 31	356 ± 35	5.9 ± 0.2	379 ± 29	267 ± 21	354 ± 31	5.5 ± 0.3
	45–60	369 ± 38	245 ± 35	386 ± 25	6.7 ± 0.3	381 ± 27	275 ± 33	344 ± 29	6.5 ± 0.2	392 ±28	252 ± 36	356 ± 38	6.3 ± 0.3	367 ± 29	254 ± 22	379 ± 33	5.9 ± 0.3
ML	0–5	200 ± 32	470 ± 32	330 ± 35	6.3 ± 0.2	180 ± 21	470 ± 19	350 ± 28	6.1 ± 0.3	230 ± 21	400 ± 32	370 ± 23	6.0 ± 0.3	250 ± 28	410 ± 32	340 ± 29	5.8 ± 0.2
	5–15	190 ± 33	430 ± 29	380 ±29	6.3 ± 0.3	190 ± 25	440 ± 23	370 ± 25	6.3 ± 0.3	250 ± 28	380 ± 36	370 ± 21	6.3 ± 0.3	230 ± 29	420 ± 33	350 ± 31	6.0 ± 0.2
	15–30	220 ± 29	450 ± 29	330 ± 28	6.5 ± 0.3	190 ± 28	420 ± 28	390 ± 25	6.3 ± 0.3	210 ± 29	400 ± 33	390 ± 29	6.5 ± 0.3	230 ± 23	410 ± 36	360 ± 33	6.2 ± 0.2
	30–45	200 ± 36	450 ± 32	350 ± 33	6.5 ± 0.3	220 ± 23	410 ± 25	370 ± 29	6.5 ± 0.2	220 ± 31	380 ± 29	400 ± 32	6.5 ± 0.3	240 ± 19	370 ± 28	390 ± 29	6.5 ± 0.2
	45–60	170 ± 37	450 ± 33	380 ± 29	6.7 ± 0.2	200 ± 28	410 ± 23	390 ± 22	6.7 ± 0.2	230 ± 27	370 ± 33	400 ± 31	6.7 ± 0.2	210 ± 22	370 ± 29	420 ± 27	6.5 ± 0.3
SG	0–5	320 ± 19	480 ± 28	200 ± 33	7.0 ± 0.3	360 ± 21	410 ± 32	230 ± 29	7.2 ± 0.3	350 ± 23	430 ± 23	220 ± 33	6.9 ± 0.3	310 ± 32	460 ± 22	230 ± 32	6.9 ± 0.3
	5–15	330 ± 21	450 ± 23	220 ± 23	7.2 ± 0.2	350 ± 24	420 ± 37	230 ± 24	7.4 ± 0.2	340 ± 28	420 ± 32	240 ± 35	7.0 ± 0.3	300 ± 29	460 ± 19	240 ± 27	7.0 ± 0.2
	15–30	300 ± 27	460 ± 27	240 ± 33	7.2 ± 0.2	300 ± 27	480 ± 35	220 ± 23	7.5 ± 0.3	290 ± 19	470 ± 33	240 ± 38	7.9 ± 0.3	270 ± 28	490 ± 34	240 ± 29	7.1 ± 0.3
	30–45	310 ± 23	390 ± 22	300 ± 31	7.7 ± 0.3	320 ± 25	430 ± 33	250 ± 28	7.9 ± 0.2	290 ± 24	450 ± 29	260 ± 29	7.9 ± 0.3	280 ± 33	450 ± 28	270 ± 27	7.8 ± 0.2
	45–60	270 ± 26	410 ± 31	320 ± 29	8.1 ± 0.3	300 ± 21	420 ± 37	280 ± 21	8.3 ± 0.3	290 ± 19	430 ± 35	280 ± 28	8.4 ± 0.2	290 ± 26	440 ± 21	270 ± 28	8.4 ± 0.3

Table A8. Bulk Density (BD) and rock fragments (RF) percentage in the different soil layers and successional stages of each site. Values represent the mean ± standard deviation (n = 3).

		Successional Stages							
Area	**Depth**	**T0**		**T1**		**T2**		**T3**	
	cm	**BD Mg m^{-3}**	**RF %**	**BD Mg m^{-3}**	**RF %**	**BD Mg m^{-3}**	**RF %**	**BD Mg m^{-3}**	**RF %**
DC	0–5	0.6 ± 0.1	0 ± 0	0.5 ± 0.1	0 ± 0	0.6 ± 0.2	8 ± 2	0.6 ± 0.1	1 ± 0
	5–15	1.0 ± 0.2	0 ± 0	0.9 ± 0.2	3 ± 1	1.3 ± 0.3	6 ± 1	1.2 ± 0.2	6 ± 1
	15–30	1.1 ± 0.2	2 ± 1	1.4 ± 0.4	7 ± 2	1.2 ± 0.3	5 ± 0.1	1.1 ± 0.3	12 ± 2
	30–45	1.1 ± 0.3	11 ± 5	1.2 ± 0.2	9 ± 3	1.2 ± 0.1	10 ± 0.2	1.2 ± 0.2	16 ± 3
	45–60	1.1 ± 0.2	12 ± 4	1.2 ± 0.2	19 ± 5	1.1 ± 0.3	11 ± 0.3	1.3 ± 0.3	11 ± 3
FC	0–5	1.1 ± 0.1	22 ± 8	0.8 ± 0.1	20 ± 3	0.9 ± 0.1	28 ± 7	0.9 ±0.2	20 ± 10
	5–15	1.4 ± 0.2	23 ± 6	1.3 ± 0.2	26 ± 8	1.1 ± 0.2	27 ± 12	1.1 ± 0.1	22 ± 4
	15–30	1.3 ± 0.1	27 ± 4	1.3 ± 0.2	34 ± 6	1.2 ± 0.2	31 ±3	1.2 ± 0.2	25 ± 5
	30–45	1.3 ± 0.3	26 ± 3	1.4 ± 0.2	26 ± 8	1.2 ± 0.3	32 ± 4	1.3 ± 0.3	23 ± 3
	45–60	1.3 ± 0.3	27 ± 5	1.4 ± 0.3	26 ± 7	1.3 ± 0.2	34 ± 6	1.3 ± 0.2	27 ± 6
LG	0–5	0.7 ± 0.1	11 ± 8	0.7 ± 0.1	15 ± 5	0.6 ± 0.1	15 ± 6	0.9 ± 0.2	43 ± 8
	5–15	1.2 ± 0.2	37 ± 9	1.2 ± 0.2	40 ± 6	1.0 ± 0.2	37 ± 7	1.0 ± 0.2	52 ± 11
	15–30	1.2 ± 0.3	38 ± 12	1.2 ± 0.3	37 ± 5	0.9 ± 0.2	46 ± 5	1.0 ± 0.1	54 ± 4
	30–45	1.1 ± 0.2	49 ± 15	1.3 ± 0.2	38 ± 14	1.0 ± 0.3	42 ± 8	1.1 ± 0.2	55 ± 3
	45–60	1.3 ± 0.2	46 ± 11	1.3 ± 0.2	31 ± 4	1.0 ± 0.2	33 ± 6	1.2 ± 0.2	53 ± 6
ML	0–5	0.7 ± 0.2	43 ± 15	0.8 ± 0.1	39 ± 7	0.7 ± 0.1	27 ± 7	0.7 ± 0.1	37 ± 13
	5–15	1.1 ± 0.1	47 ± 8	0.9 ± 0.1	31 ± 13	0.9 ± 0.1	42 ± 6	1.0 ± 0.2	53 ± 12
	15–30	1.1 ± 0.2	51 ± 5	0.9 ± 0.2	28 ± 17	1.0 ± 0.2	44 ± 7	1.0 ± 0.2	51 ± 13
	30–45	1.0 ± 0.2	0.0	1.0 ± 0.2	28 ± 15	1.0 ± 0.2	42 ± 10	1.1 ± 0.1	7 ± 10
	45–60	1.2 ± 0.3	0.0	1.0 ± 0.2	29 ± 12	1.2 ± 0.3	47 ± 9	1.1 ± 0.2	46 ± 9
SG	0–5	0.9 ± 0.1	19 ± 2	0.7 ± 0.1	19 ± 8	0.6 ± 0.1	34 ± 5	0.7 ± 0.1	37 ± 5
	5–15	1.0 ± 0.2	25 ± 8	0.7 ± 0.2	22 ± 6	0.8 ± 0.2	45 ± 4	0.8 ± 0.2	44 ± 7
	15–30	1.1 ± 0.2	17 ± 3	0.9 ± 0.2	27 ± 3	1.2 ± 0.2	55 ± 8	1.2 ± 0.3	49 ± 9
	30–45	1.2 ± 0.2	25 ± 5	1.2 ± 0.2	36 ± 6	1.2 ± 0.3	62 ± 5	1.3 ± 02	59 ± 4
	45–60	1.4 ± 0.3	31 ± 4	1.4 ± 0.3	39 ± 5	1.3 ± 0.2	65 ± 9	1.3 ± 0.2	61 ± 7

Table A9. Soil organic carbon concentration (g C kg^{-1}) in the different layers and chronosequence stages of each site. Values are the mean of 3 composite samples (n = 25) per layer ± standard deviation. Letters indicate significant differences (Tukey test $p < 0.05$) in the same layer among stages. No letters indicate no significant difference. DC = Danta di Cadore; FC = Falcade; LG = Longarone; ML = Mel; SG = Santa Giustina.

		Successional Stages			
Site	**Layer**	**T0**	**T1**	**T2**	**T3**
	cm	**g C kg^{-1} ± SD**	**g C kg^{-1} ± SD**	**g C kg^{-1} ± SD**	**g C kg^{-1} ± SD**
DC	0–5	61.3 ± 5.0a	87.6 ± 8.1b	61.7 ± 7.8a	75.8 ± 4.2c
	5–15	38.8 ± 3.4a	53.8 ± 4.3b	52.7 ± 3.2b	27.9 ± 4.0a
	15–30	20.7 ± 3.5	21.2 ± 5.9	22.0 ± 1.0	21.3 ± 2.1
	30–45	19.8 ± 1.1	18.0 ± 1.0	16.3 ± 1.2	13.7 ± 3.2
	45–60	20.7 ± 2.1a	5.5 ± 0.7b	6.7 ± 1.4b	8.3 ± 3.6b
FC	0–5	105.5 ± 11.8	116.3 ± 9.7	139.6 ± 13.6	100.2 ± 5.8
	5–15	80.8 ± 8.3a	97.8 ± 1.3a	91.1 ± 8.2a	67.7 ± 5.9b
	15–30	61.7 ± 5.6a	92.7 ± 4.6b	95.8 ± 6.0b	73.8 ± 9.4a
	30–45	83.4 ± 6.6a	93.7 ± 3.0a	87.4 ± 8.7a	63.3 ± 8.5b
	45–60	72.2 ± 6.3a	79.9 ± 4.7a	89.6 ± 5.6a	56.2 ± 5.2b
LG	0–5	113.6 ± 9.7	100.4 ± 8.4	108.3 ± 11.4	117.3 ± 8.8
	5–15	77.3 ± 5.1a	56.5 ± 9.6b	60.9 ± 8.9b	82.9 ± 7.0a
	15–30	48.0 ± 6.0	42.8 ± 4.0	62.9 ± 7.0	51.5 ± 7.9
	30–45	58.1 ± 8.1a	64.2 ± 9.5a	80.2 ± 9.0b	24.3 ± 3.3c
	45–60	73.9 ± 7.9a	67.5 ± 7.1a	72.9 ± 7.7a	33.1 ± 6.9b
ML	0–5	83.9 ± 13.7	101.1 ± 13.2	92.3 ± 6.8	99.8 ± 7.3
	5–15	51.6 ± 4.1	51.9 ± 5.7	49.5 ± 6.9	59.1 ± 8.4
	15–30	39.9 ± 4.6	48.6 ± 3.4	35.3 ± 8.4	40.2 ± 6.7
	30–45	25.2 ± 8.9	30.0 ± 7.0	18.9 ± 2.4	22.9 ± 7.6
	45–60	18.1 ± 3.5	16.7 ± 3.9	18.9 ± 4.6	27.5 ± 6.5
SG	0–5	70.0 ± 5.6a	70.7 ± 1.5a	54.3 ± 8.6b	71.7 ± 2.5a
	5–15	40.7 ± 3.8a	53.7 ± 4.2a	51.7 ± 4.2a	27.0 ± 1.7b
	15–30	22.0 ± 1.0	22.3 ± 3.1	23.7 ± 4.2	21.3 ± 2.5
	30–45	20.7 ± 2.1	19.0 ± 2.0	16.0 ± 2.9	14.7 ± 4.6
	45–60	21.3 ± 2.5a	6.3 ± 4.6b	7.3 ± 3.5b	8.3 ± 3.2b

Table A10. Soil organic carbon stock (Mg C ha^{-1}) in the different soil compartments (organic layer, topsoil, subsoil, whole mineral profile) of each site. Values are the mean of 3 composite samples (n = 25) per layer ± standard deviation. Letters indicate significant differences (Tukey test $p < 0.05$) in the same soil compartment among stages. In each line, different letters indicate a significant difference (Tukey test $p < 0.05$) between the same layers from different stages. No letters indicate no significant difference. DC = Danta di Cadore; FC = Falcade; LG = Longarone; ML = Mel; SG = Santa Giustina.

		Successional Stages			
Site	**Depth**	**T0**	**T1**	**T2**	**T3**
	cm	**Mg C ha^{-1} ± SD**	**Mg C ha^{-1} ± SD**	**Mg C ha^{-1} ± SD**	**Mg C ha^{-1} ± SD**
DC	Organic H.	0	0	0	12.8 ± 5.4
	0–30	91.1 ± 4.7a	110.3 ± 11.6ab	121.0 ± 23.1b	87.9 ± 1.5a
	30–60	58.7 ± 4.4a	36.6 ± 4.1b	37.3 ± 3.7b	35.6 ± 4.3b
	0–60	149.8 ± 6.5a	146.9 ± 12.3a	158.4 ± 23.4a	123.5 ± 7.1b
FC	Organic H.	0	0	0	7.0 ± 1.4
	0–30	217.1 ± 11.4	256.0 ± 30.0	224.1 ± 7.7	194.3 ± 26.7
	30–60	233.7 ± 30.9a	275.4 ± 27.0a	217.9 ± 8.5a	164.6 ± 21.6b
	0–60	450.8 ± 32.9a	531.4 ± 40.3b	441.9 ± 11.5a	358.9 ± 34.4c
LG	Organic H.	0	0	0	6.8 ± 3.3
	0–30	129.7 ± 21.1	116.7 ± 9.1	110.6 ± 18.7	91.6 ± 25.0
	30–60	115.2 ± 21.0a	148.4 ± 21.4a	128.3 ± 9.5a	44.2 ± 8.0b
	0–60	245.0 ± 29.8a	265.2 ± 23.3a	238.8 ± 21.0a	135.8 ± 26.3b

Table A10. *Cont.*

Site	Depth	Successional Stages T0	T1	T2	T3
	cm	Mg C ha^{-1} ± SD	Mg C ha^{-1} ± SD	Mg C ha^{-1} ± SD	Mg C ha^{-1} ± SD
ML	Organic H.	0	0	0	9.9 ± 3.1
	0–30	74.6 ± 10.1	84.5 ± 6.7	77.8 ± 5.1	81.6 ± 14.5
	30–60	65.6 ± 23.4a	49.9 ± 18.3ab	31.9 ± 8.3b	35.4 ± 7.6b
	0–60	140.2 ± 25.5	134.4 ± 19.5	109.7 ± 9.8	116.9 ± 16.4
SG	Organic H.	0	0	0	20.7 ± 6.3
	0–30	87.0 ± 6.1a	61.4 ± 14.7a	49.9 ± 2.2b	41.1 ± 5.7b
	30–60	44.7 ± 8.9a	19.7 ± 2.2b	16.9 ± 4.4b	17.9 ± 4.9b
	0–60	131.7 ± 10.7a	71.1 ± 14.8b	66.8 ± 4.9b	59.0 ± 7.5b

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