ORIGINAL ARTICLE

Soil climate regulation services: high SOC stock in Podzols and Umbrisols in an alpine grassland (Valle Adamé, Italy)

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Abstract

The United Nations Sustainable Development Goals include soil conservation as an urgent climate action to be taken; alpine grassland soils, rich in organic matter and particularly vulnerable to climate change, require special attention. In the upper Adamé valley (Italy), the effects of soil and vegetation types and environmental parameters, on soil carbon (SOC) stock and other soil properties were evaluated. Sampling points were chosen starting from the main vegetation types (dominant species: *Rhododendron ferrugineum*, *Nardus stricta*, *Festuca luedii*, *Adenostyles leucophylla* and *Salix herbacea*). For each vegetation type, five plots were selected, within which three soil minipits were described and sampled by layers (0–10 cm, 10–20 cm and 20–40 cm), at 75 georeferenced points. The results highlighted that: (1) Podzols and Umbrisols showed high capacity to store OC in the top 40 cm (17.3 ± 8.2 kg m^{-2}), whereas Fluvisols and Leptosols demonstrated a low capacity (5.0 ± 3.5 kg m^{-2}); (2) topographical factors indirectly affected the variability of the SOC stock by influencing the spatial distribution of vegetation; (3) 74% of the SOC stock was sequestered in the upper 0–20 cm layer; (4) regardless of soil type, *Festuca* and *Salix* were the vegetation types that mostly contributed to the surface SOC enrichment, followed by *Rhododendron*, *Nardus* and *Adenostyles*. Following climate change, a shift of the *Salix* and *Nardus* vegetation types in favour of the *Rhododendron* type is expected in the short to medium term. As a consequence, a possible reduction in the effectiveness of the climate regulation service provided by the soils may occur.

Keywords Soil organic carbon stock · Soil type · Spatial variability · Plant community · Vegetation upward migration · Mountain ecosystem

Introduction

Soils represent the largest organic carbon reservoir in the terrestrial biosphere, globally exceeding the total carbon pool of vegetation and the atmosphere (Bhattacharya et al. 2016).

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Most studies estimate the global amount of soil organic carbon (SOC) to be around 1400–1500 Pg C in the top 100 cm (Scharlemann et al. 2014; Batjes 2016).

Among the ecosystem services they provide, soils play a key role in climate regulation through the sequestration of atmospheric carbon dioxide (CO_2) and its storage as organic carbon (Jónsson and Davídsdóttir 2016).

The Sustainable Development Goals (SDGs) defined by the United Nations in 2015 include soil conservation as an urgent climate action to be taken, with the goal of preserving its multifunctional role.

Indeed, studies on the potential of soils to act as carbon sinks and mitigate climate change have increased in recent decades. Studies on alpine soils have also increased, as they are notoriously rich in organic matter (Zhu et al. 2019) and particularly susceptible to climate change, in terms of increased erosion, changes in microbial community structure and activity, and rising CO_2 emissions (Garcia-Pausas et al. 2007; Sjögersten et al. 2011).

Soil carbon content depends on many factors. Most studies agree that vegetation is the environmental variable that mostly influences the quantity, quality, and distribution of SOC (Kumar et al. 2017). Indeed, vegetation, with the biomass it holds, is the main contributor to soil organic matter, and once processed by the soil biota in relation to abiotic factors, it determines the formation and accumulation of SOC (Kuznetsova 2022). Variations in vegetation composition can lead to large variations in the amount and type of soil organic matter (Drewnik et al. 2016). For example, in mountain regions, broadleaf forests, coniferous forests, and grasslands have different rates of SOC production, accumulation, and decomposition (Oueslati et al. 2013). In particular, the SOC stock of alpine grasslands and broadleaf forests is higher compared to alpine coniferous forest soils (Canedoli et al. 2020). Many authors have investigated the relationship between SOC and vegetation type, but only a few have worked at the level of the plant community (Ferré et al. 2020; Yimer et al. 2006), investigating the effect of the mosaic of plant communities on SOC content (Zhao et al. 2021).

However, SOC is also greatly affected by topographical (aspect, elevation, and slope), pedoclimatic and pedological factors (temperature, water content, chemical, physical, and biological characteristics of soil).

As regards the relationship between SOC stocks and soil types, the existing papers have mostly been carried out at small scale, giving great importance to land use and land cover (Mendoza-Vega et al. 2003; Munoz-Rojas et al. 2012; Wiesmeier et al. 2015). Only Conforti et al. (2016) have worked on a larger scale, in a nature reserve in Calabria.

Climatic conditions and, therefore, climate change, can also strongly influence the carbon cycle, alter carbon fluxes, and consequently affect the carbon storage capacity of soils. Several studies have investigated the response of SOC to warming (Li et al. 2021). Many of these have been conducted in the alpine regions of the Tibetan Plateau, considered one of the most sensitive areas to climate change (Chen et al. 2020). These studies have shown that both C and N cycles are sensitive to warming at the ecosystem level, but the observed changes in total C and N stocks are minimal, so that warming effects are likely to offset each other. In fact, on the one hand, warming increases plant biomass, resulting in higher inputs of C and N into the soil, and on the other hand, it stimulates soil respiration, leading to large losses of C as CO_2 to the atmosphere. Contrary to these results, other authors have observed an overall loss of carbon, due to the predominant effect of warming on the microbial activity of decomposing organic matter (Hagedorn et al. 2010; Streit et al. 2014; Melillo et al. 2017).

Studies on SOC content and its relationships with environmental factors are particularly complex in mountain areas, which are characterized by high local variability in soil environment, topography, and microclimate. This variability influences the carbon cycle, induces changes in soil organic matter (SOM) quality and quantity (Canedoli et al. 2020; Ferré et al. 2020) and determines a high spatial heterogeneity of SOC (Zhu et al. 2019). Particularly, elevation, aspect, slope, temperature, and water content have been reported to be the main determinants of the great variability in the spatial patterns of mountain SOC (Hoffmann et al. 2014; Zhu et al. 2019).

Elevation is the most studied topographic variable, due to its close relationship with temperature and consequently with vegetation, which develops mainly along altitudinal bands. In most cases, SOC stock (Dorji et al. 2014; Zhang et al. 2021; Zhu et al. 2019), or SOC content (Parras-Alcántara et al. 2015; Choudhury et al. 2016), has shown a positive correlation with altitude, which strongly influences the mesoclimate and turnover of vegetation types, affecting organic matter decomposition rate and plant production (Zhu et al. 2019). Specifically, the increase in SOC with altitude is explained by the decrease in temperature, which limits the microbial activity and the decomposition rate of SOM, allowing the accumulation of SOC (Parras-Alcántara et al. 2015). However, over a certain elevation, the strong reduction of vegetation cover and the soil itself would cause a decrease in the SOC stock.

Aspect affects the amount of solar radiation incident on the ground and the microclimatic characteristics of an area. Some authors (Jendoubi et al. 2019; Zhu et al. 2019) have found that south-facing soils have a lower SOC content than north-facing soils, while others (Drewnik et al. 2016; Yimer et al. 2006) have observed the opposite trend.

With regard to the gradient of slopes, previous studies observed a strong negative correlation between SOC content and increasing slopes (Jendoubi et al. 2019; Yu et al. 2020). This is due to the higher intensity of runoff processes that characterize steeper slopes compared to flat areas, where the accumulation of material is favoured (Jendoubi et al. 2019).

However, since the effects of elevation, aspect, and slope are often strongly related to each other, it is difficult to disentangle their single contribution to the SOC stock.

To date, studies on the climate regulation services of mountain soils that assess the interaction of multiple factors in influencing C stocks are quite limited. Therefore, we present here the results of a study in a valley of the Central Alps (Italy) on the climate regulation services of alpine soils. The objectives of this work were: i) the investigation of the effects of soils, vegetation types and environmental parameters on the SOC stocks and other soil properties; and ii) the formulation of hypotheses on the effects of climate change on the evolution and biodiversity of plant communities and the SOC storage.

Materials and methods

Study area

The study area (Lat: 46.1090°, Lon: 10.5260°) is located in the Valle Adamé, one of the main glacial valleys of the Adamello Group in the Central Alps (Fig. 1), which extends with a sub-planar morphology and an N–S trend for about 8 km, starting from the glacial threshold at 2000 m a.s.l. that separates it from the Val Saviore below.

From a geologic point of view (Callegari and Dal Piaz 1973), the Adamello Group is made up of a large Cenozoic batholith surrounded by a band of older crystalline metamorphic rocks. The central massif, including the highest peak (Mt. Adamello, 3539 m), is mainly made up of tonalites, quartzdiorites, and granodiorites, emplaced during the Late Eocene–Late Oligocene alpine orogenesis. The summit area of the massif hosts the Adamello glacier, the largest in the Italian Alps (about 16 km^2 in 2007; Baroni et al. 2007). During the Last Glacial Maximum, the Valle Adamé was covered by glaciers that shaped the local morphology, which was characterized by a succession of basins, steps, and glacial deposits (Baroni et al. 2014). The climate of the Valle Adamé is continental (endoalpine type), with cold winters and mild summer temperatures. The annual mean temperature at about 2200 m is 5.6 °C, and annual precipitation reaches 1350 mm in the upper Adamé Valley (Ceriani and Carelli 1999). Snow may persist locally in sheltered channels even during the late summer (Baroni et al. 2014).

Above the current tree line, the vegetation in the Valle Adamé mainly consists of *Festuca luedii* (Markgr.-Dann.) Foggi, Gr.Rossi, Parolo & Wallossek grasslands (mainly on the southern slopes), *Nardus stricta* L. pastures, and *Rhododendron ferrugineum* L. heatlands. Sites with long-lasting snow cover are characterized by alpine tundra (*Salix herbacea* L.) and by tall herbs (*Adenostyles leucophylla* (Willd.) Rchb.).

Soils are mostly acidic, rich in rock fragments, coarse-textured, and well-drained; the main soil types (IUSS Working Group WRB 2022) are Leptosols, Podzols, and Umbrisols (Sartori et al. 2005).

The study area is interested in the summer period by pasture. Dairy cattle and goats graze freely throughout the area, mainly using the pasture areas on the valley floor, which are a mosaic of fat, lean, wet and shrub pasture plots. The livestock load, evaluated in ABU (Adult Bovine Units) has not changed in the last 20 years (data of Lombardy alpine pasture census for 2000 and 2021; unpublished): 2/3 is represented by cattle and the remaining by goats.

Vegetation survey

To investigate the soil–vegetation relationship and how the SOC stock varied between the main plant communities, five vegetation types were selected according to the dominant species: 1. *Salix herbacea* (*Salix*), *Nardus stricta* (*Nardus*), *Rhododendron ferrugineum* (*Rhododendron*), *Adenostyles leucophylla* (*Adenostyles*), *Festuca luedii* (*Festuca*). The field survey took place in the second half of July 2019, when vegetation development was at its peak. For each vegetation
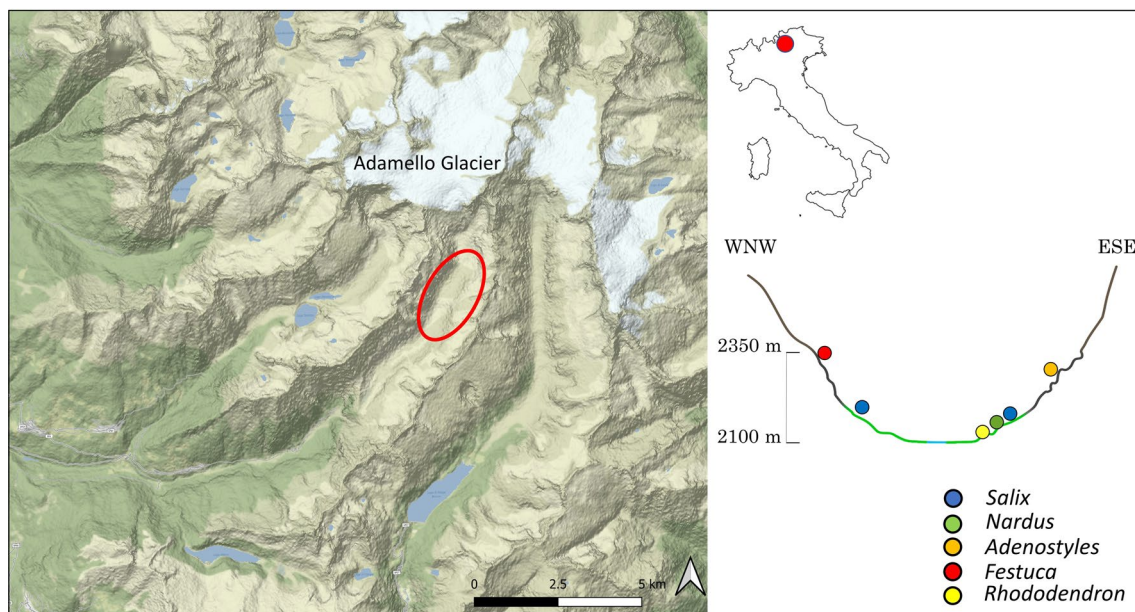

Fig. 1 Study area with schematic indication of the altitudinal range to which plots belong (plots are divided by vegetation type)

type, five plots of about 30×30 m were selected along the valley in areas where the dominant species exceeded 50% cover (Fig. 1). In each plot, three 50×50 cm sampling points were randomly selected, approximately 20 m apart, where the floristic survey was carried out, to also verify that the vegetation types were well-defined and separated before proceeding with the soil sampling.

The nomenclature follows the updated checklists of the vascular flora of Italy (Bartolucci et al. 2018), continuously updated in The Portal to the Flora of Italy (https://dryades.units.it/floritaly/) (Martellos et al. 2020).

Soil sampling and laboratory analyses

For each vegetation type, three minipits were opened and described by horizon within each of the five plots near the floristic sampling points; for each plot, only the minipit considered most representative was sampled for taxonomic classification (IUSS Working Group WRB 2022). For the evaluation of the effects of vegetation, soil types and environmental factors on SOC stock and other soil properties, soil samples were collected from the 0–10 cm, 10–20 cm and 20–40 cm layers of the 75 georeferenced minipits. In some cases, the depth reached was less than 40 cm due to the presence of the rocky substrate near the soil surface. A total of 188 mineral soil samples were collected.

For each layer, the percentage of rock fragments (RF) was visually estimated, and volumetric samples (core diameter 5 cm; sample volume 100 cm^3) were taken for the determination of bulk density (BD); the latter sampling was only carried out in the minipit considered to be the most representative, with a total of 75 core samples collected. For the BD determination, soil cores were oven dried at 105 °C for 24 h and weighed; in the presence of rock fragments, the soil volume and mass were proportionally reduced to obtain the BD of fine earth (< 2 mm diameter).

For those layers for which no core sample was obtained, site-specific empirical pedofunctions, one for each investigated layer (0–10 cm [1]; 10–20 cm [2]; 20–40 cm [3]), were used to estimate the BD value as a function of the SOC content (%):

$$y = 1.0435 \times SOC^{-0.255} \quad r^2 = 0.53, \tag{1}$$

$$y = -0.183 \times \ln(SOC) + 1.0861 \quad r^2 = 0.79, \tag{2}$$

$$y = -0.185 \times \ln(SOC) + 1.1358 \quad r^2 = 0.86. \tag{3}$$

Soil mineral samples were air dried, sieved (2 mm mesh) and analyzed to determine pH in H$_2$O (pH; soil to water ratio of 1:2.5). A fraction of each sample was further crushed, sieved to a finer mesh (0.5 mm) and analyzed for the determination of organic carbon and total nitrogen contents by dry combustion using a Flash EA 1112 NC-Soil elemental analyzer (Thermo Fisher Scientific CN, Pittsburgh, USA). The SOC content (%) was converted to SOC stock (kg m^{-2}) considering the soil BD and the percentage volume of rock fragments in each layer.

For each soil sampling point, the organic horizon (OL only) was also collected using a 33×33 cm frame, oven-dried at 70 °C for 48 h and then weighed. The organic carbon and nitrogen content of the organic samples was determined using the NC elemental analyzer and converted to content on an area basis (kg m^{-2}).

The list and abbreviations of all the parameters considered are given in Table 1.

Sampling of aboveground and root biomass

One sample of epigean biomass and one of hypogean biomass were taken per plot, in correspondence with one of the three minipits, and the floristic survey area. The same 33×33 cm frame used for the sampling of the organic horizon was used for the sampling of aboveground biomass, cutting approximately 2 cm above the ground. The collected biomass was air-dried, then put in an oven at 80 °C, weighed and expressed as weight on an area basis (kg m^{-2}).

A soil cube sample was taken to a depth of 10 cm (sample volume 1 dm^3) for the determination of the root biomass. The extraction of roots from the cores was carried out by presoaking the sample in agitation overnight in a solution of EDTA (40 g L^{-1}) to facilitate washing. After that, roots were washed, picked out, separated into three diameter classes (< 2 mm, very fine roots; 2–5 mm, fine roots; > 5 mm, coarse roots), and oven dried at 80 °C for 24 h to determine the dry masses of the root biomass, expressed as g dm^{-3}.

The organic carbon and nitrogen contents of the aboveground and belowground samples were determined using the NC elemental analyzer; the C:N ratio for roots and aboveground biomass was then calculated.

Aboveground biomass and root samples were taken for all the vegetation types, and the ratio of aboveground to belowground biomass was calculated for each, with the only exception of *Rhododendron*, which is a shrub species also characterized by dense, abundant root systems and large roots, that do not allow for proper volumetric sampling.

Ancillary data

For each minipit location, elevation, aspect and slope were extracted from the Digital Terrain Model (DTM, 5 m resolution) using QGIS software (version 3.16).

Aspect was converted into Northness and Eastness Index (cosine and sine of the aspect expressed in radians, respectively).

Table 1 Investigated soil properties and types, environmental variables, vegetation types and indexes and their abbreviations

Soil properties, environmental variables, and vegetation	Unit	Abbreviation
Soil organic carbon		SOC
Soil organic carbon stock of OL horizon	kg m^{-2}	SOC$_{stockOL}$
C:N ratio of OL organic horizon	Ratio	CN$_{OL}$
Aboveground biomass	kg m^{-2}	AgB
Total, very fine, fine and coarse root biomass	g dm^{-3}	totRoots, vfRoots, fRoots, cRoots
Soil organic carbon stock of the 0–10 cm, 10–20 cm, 20–40 cm, 0–20 cm and 0–40 cm mineral soil layers	kg m^{-2}	SOC$_{stock1}$, SOC$_{stock2}$, SOC$_{stock3}$, SOC$_{stock1-2}$, SOC$_{stock}$
C:N ratio of the 0–40 cm and 0–20 cm mineral soil layers		CN, CN$_{1-2}$
pH in water of the 0–20 cm and 0–40 cm mineral layers		pH$_{1-2}$, pH
Bulk density of the 0–20 cm and 0–40 cm mineral layers	g cm^{-3}	BD$_{1-2}$, BD
Water filled pore space in the 0–8 cm layer	%	WFPS
Rock fragments	%	RF
Elevation	m a.s.l.	Elev
Eastness and Northness Indexes		Eastness, Northness
Podzols		PZ
Leptosols		LP
Umbrisols		UM
Fluvisols		FL
Adenostyles type		Al
Festuca type		Fl
Rhododendron type		Rf
Nardus type		Ns
Salix type		Sh
Plant species diversity expressed as Shannon H'		α-Shann
Plant species richness expressed as number of plant species		α-Rich
Plant species diversity expressed as species turnover according to the Bray–Curtis index		β-BrayCurtis

In addition, the soil water content was measured at each minipit location in the 0–8 cm layer using a portable TDR system (IMKO Micromodultechnik, GmbH, Ettlingen, Germany) and then converted (using total soil porosity, totPor) to water-filled pore space (WFPS). The totPor was previously calculated from $\frac{PD-BD}{PD}$, where PD (g cm^{-3}) is the soil particle density (PD $= 2.65 - 0.02 \times SOC(\%) \times 1.724$).

Statistical analyses

The similarity percentage procedure (SIMPER analysis) was performed to assess the species contribution across vegetation types using the average Bray–Curtis dissimilarity index (Table 2). Analyses of similarity (one-way ANOSIM; Bray–Curtis index; 10,000 permutations) were used on the full species data set to test for differences in species composition between the vegetation types before starting soil sampling.

To evaluate the effects of vegetation, soil types and environmental factors on SOC stock and the other soil properties, a linear mixed effect model (LME) procedure was run in the R environment (version 4.2.2; R Core Team 2022)

with soil type, vegetation type or environmental factors as fixed effects and "plot" and "soil type" (if not used as a fixed effect) as random effects, with plot nested within soil.

To identify differences in biodiversity between vegetation types, the same LME procedure used for soil properties was also performed, with vegetation type as a fixed effect and plot, nested within the soil type, as a random effect.

To analyse the relationships among plant species, soil properties (0–20 cm layer) and environmental variables, the canonical correspondence analysis (CCA) ordination method was used. The CCA was performed with the CANOCO software, version 4.5 (Ter Braak et al. 2002). Before CCA, correlation analysis (Spearman's rho) was carried out to reduce the number of variables and noise in the variance components. One of each pair of highly correlated variables, with a correlation coefficient ≥ 0.75, was eliminated from the analysis (Perez-Riverol et al. 2017). During the CCA analysis, variables showing a variance inflection factor (VIF) higher than 10 were also removed. The significance of the variables was tested using permutation tests ($N = 999$).

Particularly at first, we performed a CCA, including the selected variables. Subsequently, to assess the effect of

Table 2 SIMPER analysis of the selected vegetation types. The overall dissimilarity according to the Bray–Curtis index was 91.72

Taxon	Av. dissim	Contrib. %	Cumulative %	Salix herbacea	Rhododendron ferrugineum	Nardus stricta	Festuca luedii	Adenostyles leucophylla
Fes_lue	12.92	14.08	14.08	0	0.333	0	84	0
Rho_fer	10.98	11.97	26.06	0	77	0	0	0
Ade_leu	9.43	10.28	36.34	0	0	0	0	72.3
Nar_str	7.944	8.661	45	1.13	2.93	48.5	0.6	0
Sal_her	6.12	6.672	51.67	38.3	0	0.133	0	0
Imp_ost	3.878	4.228	55.9	0	0	0	0	30.5
Mut_ado	3.772	4.113	60.01	9.8	8.87	8.17	0.533	15.6
Sco_hel	3.544	3.863	63.87	11.3	8.8	13.4	1.27	0
Fes_rub	3.34	3.641	67.52	0	0.867	2.37	6.67	16.9
Pot_aur	2.997	3.267	70.78	13.1	4.2	7.6	0.0333	0
Hom_alp	2.314	2.523	73.31	9.5	7	3.53	0.167	0
Car_sem	1.874	2.043	75.35	1.13	2.87	3.03	6.87	0
Vac_myr	1.808	1.971	77.32	0	10.6	0.667	2.4	0
Vac_uli	1.64	1.788	79.11	0.467	3.2	0.5	8	0
Bis_viv	1.617	1.763	80.87	6.2	1.27	5.13	0	0

Fes_lue: *Festuca luedii*; *Rho_fer*: *Rhododendron ferrugineum*; *Ade_leu*: *Adenostyles leucophylla*; *Nar_str*: *Nardus stricta*; *Sal_her*: *Salix herbacea*; *Imp_ost*: *Imperatoria ostruthium* L.; *Mut_ado*: *Mutellina adonidifolia* (J.Gay) Gutermann; *Sco_hel*: *Scorzoneroides helvetica* (Mérat) Holub; *Leu_alp*: *Leucanthemopsis alpina* (L.) Heywood; *Fes_rub*: *Festuca rubra* L.; *Pot_aur*: *Potentilla aurea* L.; *Hom_alp*: *Homogyne alpina* (L.) Cass.; *Car_sem*: *Carex sempervirens* Vill.; *Vac_myr*: *Vaccinium myrtillus* L.; *Vac_uli*: *Vaccinium uliginosum L*; *Bis_viv*: *Bistorta vivipara* (L.) Delarbre

topographical variables on the variance of the other environmental variables (especially C stock), we carried out a partial-CCA considering elevation, slope and aspect as covariates.

Results

Vegetation

The selected vegetation types exhibited differences in species composition and relative abundance, as also highlighted by the ANOSIM analysis, using the Bray–Curtis index (mean rank within = 308.9; mean rank between = 1640; r 0.9592; $p < 0.0001$). All pairwise comparisons between groups exhibited significant differences ($p < 0.01$ for all comparisons after the Bonferroni correction). According to the SIMPER analysis (Table 2), the total dissimilarity among groups was 91.72 (Bray–Curtis index). Besides the dominant species characterizing the five vegetation types, the five species that mostly contributed to the dissimilarity among groups were (values above 3%): *Imperatoria ostruthium*, *Mutellina adonidifolia*, *Scorzoneroides helvetica*, *Festuca rubra* and *Potentilla aurea*.

The cumulative vegetation cover was the highest in the *Adenostyles* type and the lowest in the *Nardus* and *Salix* types ($F = 11.3267$; $p < 0.0001$; Fig. SM1).

Overall, the α-diversity among groups was similar, except for *Festuca* type that showed the lowest value of richness ($F = 15.27$; $p < 0.0001$) and Shannon index ($F = 11.27$; $p < 0.0001$; Fig. SM1). On the other hand, β-diversity according to the Bray–Curtis dissimilarity was the highest in *Festuca* and *Salix* types compared to the other three vegetation types ($F = 5.703$; $p < 0.0038$; Fig. SM1).

Soil

Soil types

Based on the WRB classification (IUSS Working Group WRB 2022), the main soil types were Leptosols, Umbrisols, Podzols and Fluvisols (Table SM1).

Leptosols, thin soils, developed on boulders on very steep slopes, showed a high rock fragment content and an umbric horizon (Umbric Skeletic Leptosols; 9–25 cm thick). They were mainly located on the NW-facing slopes, under the *Adenostyles* vegetation type, and to a lesser extent on the lower slopes at the junction with the valley floor, under the *Rhododendron* vegetation type.

On the SE-facing slopes, under the *Festuca* vegetation type, we found the deepest soils among those studied: Umbric Entic Podzols (45–47 cm thick) and Cambic Umbrisols (42–45 cm thick).

Podzols (Entic Podzol; 30–45 cm thick) and Umbrisols (30–40 cm thick with evidence of colluvium and a

protospodic horizon), were also found under the *Salix* vegetation type.

On the lower slope and at the junction with the valley floor, where *Nardus* and *Rhododendron* types predominated, Dystric Fluvisols, Podzols and Umbrisols were found.

SOC stock and other soil properties by soil types

The average SOC stock in the 0–40 cm layer (SOC_{stock}) was 11.7 ± 8.9 (mean $\pm$ SD) kg m^{-2} with Podzols and Umbrisols showing a significantly higher SOC_{stock} than Fluvisols and Leptosols (Fig. 2; $F_{3,47} = 6.07$, $p < 0.01$, $R^2 = 0.80$).

SOC_{stock} by soil type and overlying vegetation are reported in Table SM2.

In Podzols, the highest SOC stocks were found under *Salix*, but mainly under *Festuca*; Umbrisols with the highest SOC_{stock} were found mainly under *Nardus*, *Salix* and *Festuca*. Among the Leptosols, which contained lower SOC_{stock} than the other soil types due to their limited thickness, the richest ones were found under *Festuca*.

Statistically significant differences among soil types were found for the C:N ratio of the 0–40 cm layer (CN) ($F_{3,47} = 6.36$, $p < 0.01$, $R^2 = 0.64$), which was lower in Fluvisols (mean $\pm$ SD: 11.7 ± 1.4) than in Leptosols (14.2 ± 1.6), Umbrisols (13.8 ± 1.3) and Podzols (15.2 ± 1.8), but not for pH (Fig. 2 and Table SM3). Among the investigated soil types, the thin Leptosols had the highest rock fragment

content, statistically different from the other types in the 0–20 cm layer ($F_{3,47} = 8.34$, $p < 0.001$, $R^2 = 0.40$).

Effects of geomorphology on SOC stock

The investigated plots were located in the upper part of the valley, between 2000 and 2350 m, mainly facing NW and SE and on slopes ranging from 4° to 41° (Table SM3).

Considering the effects of morphology on SOC_{stock} (Table 3) the LME model showed that the stock increased with increasing altitude ($F_{1,45} = 7.19$, $p < 0.05$) and decreasing Northness Index ($F_{1,45} = 6.44$, $p < 0.05$), while it showed no relationship with Eastness Index ($F_{1,45} = 0.34$, $p = 0.56$) and slope ($F_{1,45} = 1.94$, $p = 0.17$).

Plant–soil relationships

Vegetation was observed to influence the SOC stock mainly in the first investigated layer (SOC_{stock1}) and partly in the second one (SOC_{stock2}), while it had no effect in the third layer (SOC_{stock3}; Table 4). *Festuca* and *Adenostyles* showed higher SOC_{stock1} compared to the other types; the SOC_{stock2} under *Festuca* was significantly higher than that of the other vegetation types, but not different from that of *Salix,* which only differed from that of *Adenostyles*.

In this regard, it should be noted that, according to the field description and the laboratory determination (the

Fig. 2 Soil carbon stock, pH, C:N ratio and rock fragments content of the 0–40 cm layer by soil types. For abbreviations refer to Table 1. Box plot legend: middle point: median, box: IQR range, whisker: non-outlier range
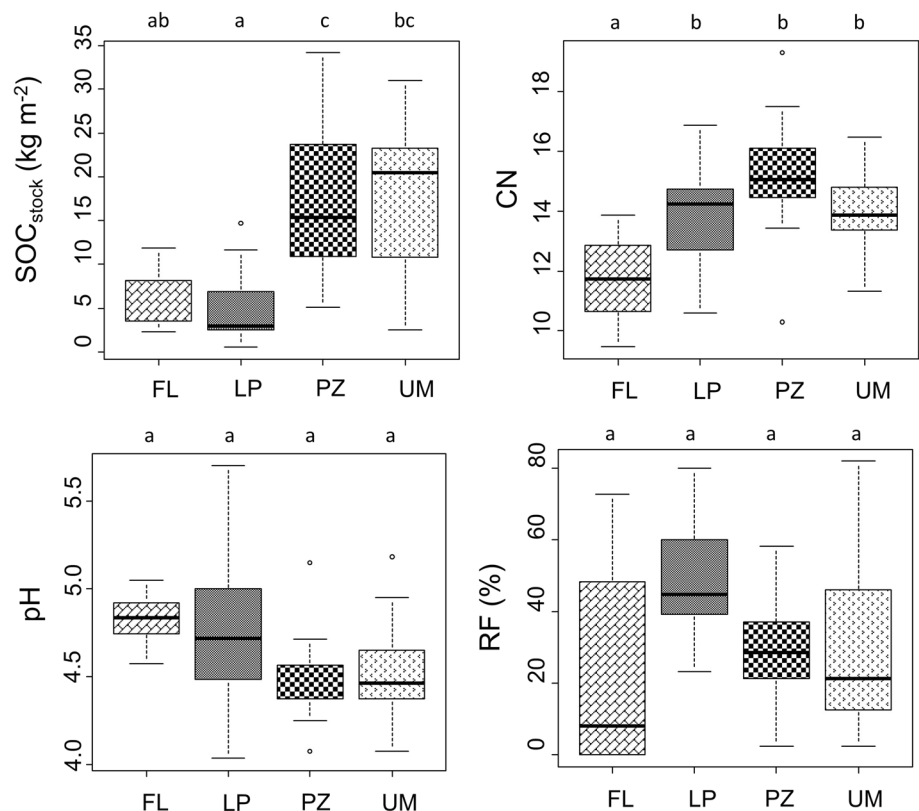
Table 3 SOC stock (0–40 cm) relationships with morphological variables (slope, elevation and aspect expressed as Northness and Eastness Indexes)

	Intercept	Elev.	Northness	Slope	Eastness
SOC$_{stock}$					
Value	− 105.179	0.054	− 7.459	− 0.164	1.052
Std. error	43.673	0.020	2.938	0.117	1.795
DF	45	45	45	45	45
t value	− 2.408	2.682	− 2.538	− 1.393	0.586
p value	**0.020**	**0.010**	**0.015**	0.170	0.561
$R^2_{marginal}$	0.39				
$R^2_{conditional}$	0.82				

p values < 0.05 are in bold

Table 4 Linear mixed model results of SOC stock of each investigated layer; vegetation type was fitted as fixed factor, while "plot" and "soil type" as random effects, with "soil" nested within "plot"

	Intercept	NS	RF	SH	FL	Post-hoc analysis (Tukey test)	Ns	Al	Sh	Fl
SOC$_{stock1}$										
Value	2.322	1.922	2.106	5.117	5.216		Ns	Al	Sh	Fl
Std. error	0.624	0.882	0.882	0.882	0.882	Al	0.188			
DF	50	17	17	17	17	Sh	**0.002**	**< 0.001**		
t value	3.719	2.177	2.386	5.795	5.908	Fl	**0.001**	**0.001**	**0.003**	
p value	**0.000**	**0.044**	**0.029**	**0.000**	**0.000**	Rf	0.999	0.119	**0.005**	**0.003**
R^2m	0.56									
R^2c	0.75									
SOC$_{stock2}$										
Value	0.693	2.377	0.787	5.241	6.301		Ns	Al	Sh	Fl
Std. error	1.145	1.409	1.414	1.409	1.409	Al	0.439			
DF	42	18	18	18	18	Sh	0.097	**0.001**		
t value	0.605	1.686	0.556	3.718	3.718	Fl	**0.006**	**< 0.001**	0.436	
p value	0.548	0.108	0.584	**0.002**	**0.000**	Rf	0.649	0.980	**0.001**	**< 0.001**
R^2m	0.53									
R^2c	0.77									
SOC$_{stock3}$										
Value	3.240		− 1.947	1.019	4.354					
Std. error	1.820		2.627	2.439	2.428					
DF	31		14	14	14					
t value	1.780		− 0.741	0.418	1.793					
p value	0.084		0.470	0.682	0.094					
R^2m	0.22									
R^2c	0.64									

p values < 0.05 are in bold

For abbreviations refer to Table 1. R^2m: marginal *r*-sqaured; R^2c: conditional *r*-squared

latter only for the first layer), the biomass of the root system was mainly in the first layer, with differences among vegetation types, and remained high in the second layer only under *Festuca* and *Salix* (Table 5). The differences among the vegetation types were not only limited to the SOC stock of the 0–20 cm layer (SOC$_{stock1-2}$: $F_{4,18} = 12.14$, $p < 0.001$, $R^2 = 0.80$), but also concerned other soil properties (Fig. 3), such as the SOC stock and C:N ratio of OL horizon (SOC$_{stockOL}$: $F_{4,18} = 10.71$, $p < 0.001$, $R^2 = 0.59$; CN$_{OL}$: $F_{4,15} = 27.72$, $p < 0.001$, $R^2 = 0.68$), the C:N ratio and pH up to 20 cm depth (CN$_{1-2}$: $F_{4,18} = 3.21$, $p < 0.05$, $R^2 = 0.63$; pH$_{1-2}$: $F_{4,18} = 9.16$, $p < 0.001$, $R^2 = 0.70$), the WFPS ($F_{4,18} = 13.05$, $p < 0.001$, $R^2 = 0.57$), the aboveground biomass and the ratio of aboveground biomass to total root biomass (AgB: $F_{3,16} = 9.48$, $p < 0.001$, $R^2 = 0.60$; AbB:totRoots: $F_{3,14} = 22.71$, $p < 0.001$, $R^2 = 0.97$).

Regarding the organic horizon, the SOC$_{stockOL}$ under *Festuca* and *Rhodedendron* was higher than that of the other vegetation types, statistically different from *Nardus* and *Salix*; CN$_{OL}$ under *Festuca* was the highest, while

Table 5 Total, coarse, fine and very fine root density (g dm^{-3}) in the 0–10 cm layer for each vegetation type and field estimation of root amount for each investigated layer and vegetation; n.d.: not determined

Veg-etation type	vfRoots		fRoots		cRoots		totRoots		Minipit description			C:N of very fine roots
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	0–10 cm	10–20 cm	> 40 cm	
Al	15.62	8.78	3.30	2.80	1.82	1.81	20.73	12.43	Many-abundant	Absent	Absent	136 ± 3.7
Ns	9.64	3.80	0.87	0.89	–	–	10.51	4.42	Common-many	Common	Few-common	95.7 ± 13.1
Sh	11.43	3.92	0.70	0.41	0.31	0.42	12.44	3.29	Many	Common-many	Common	103.3 ± 13.2
Fl	10.91	2.90	0.16	0.17	0.33	0.74	11.40	3.27	Many	Abundant	Common	112.2 ± 4.3
Rf	n.d.		n.d.		n.d.		n.d.		Common-many	Common	Few	n.d.

C:N refers to the ratio between organic carbon and total nitrogen of very fine roots. For abbreviations refer to Table 1
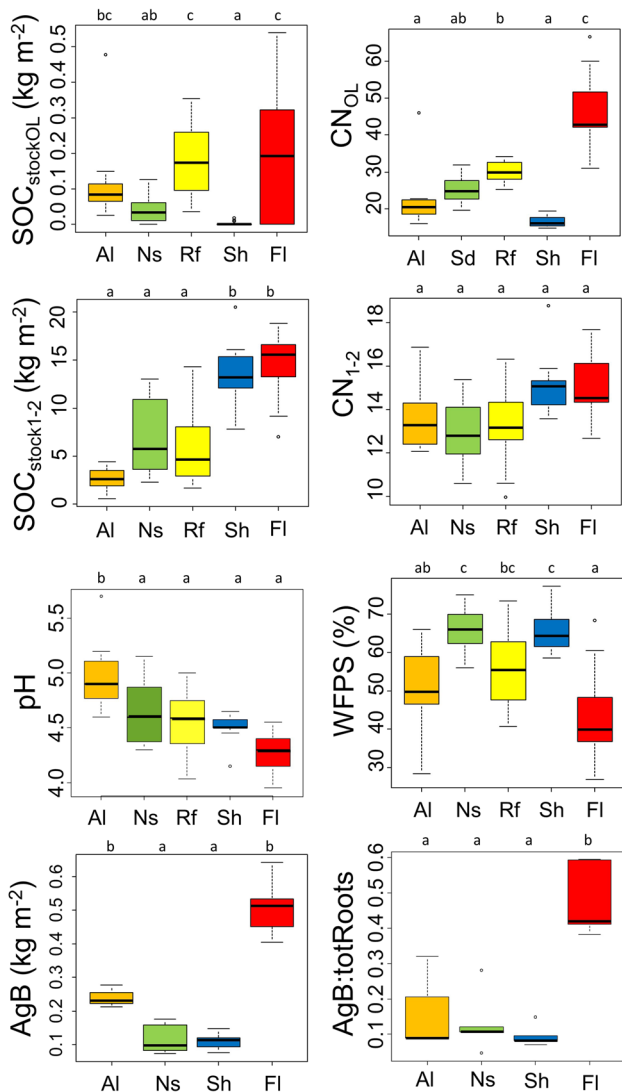
Fig. 3 SOC stock and C:N ratio of organic horizon, SOC stock, C:N ratio and pH of 0–20 cm mineral layer, WFPS, aboveground biomass, ratio between aboveground and belowground biomass by vegetation types. For abbreviations of the variables, refer to Table 1. Box plot legend: middle point: median, box: IQR range, whisker: non-outlier range

under *Salix* and *Adenostyles* was the lowest; *Rhododendron* and *Nardus* types showed intermediate values of CN.

The first 20 cm of soil under *Adenostyles* had the highest pH$_{1-2}$ (5.0 ± 0.3), statistically different from all the other vegetation types.

Concerning soil water content, *Nardus* and *Salix* prefer wetter soils, with WFPS values ranging between 60% and 70%, significantly different from those of the other vegetation types. Under *Festuca*, located on the south-facing slope, the topsoil was the driest.

Festuca and *Adenostyles* were also characterized by the highest aboveground biomass (mean ± SD: 0.51 ± 0.09 kg m^{-2} and 0.44 ± 0.28 kg m^{-2}, respectively), while no difference in root biomass in the first 10 cm was found between vegetation types, so that the ratio between above- and belowground biomass was the highest in the case of *Festuca* and the lowest for *Salix*.

The CCA analyses generally resulted in high eigenvalues and high cumulative percent variances for the species data. In both the full model and that considering covariables, the first three CCA axes explained about 60% of the variance (Table 6; Fig. 4).

In the full model, environmental variables that showed significance (p value < 0.05) and the highest levels of LambdaA score (above 0.15) were: slope (0.69), SOC$_{stock1-2}$ (0.58), elevation (0.34), soil depth (0.17).

In the biplot of the first two axes (Fig. 4a), slope and elevation were positively correlated with the *Festuca* and *Adenostyles* types and negatively correlated with the other vegetation types.

Salix, *Nardus* and *Rhododendron* were close to each other and positively correlated with soil water content, while they were negatively correlated with elevation, slope, and rock fragments. *Festuca* and *Adenostyles* were isolated from the other vegetation types. *Festuca* vegetation was positively correlated with SOC stock, elevation, and slope, while it was inversely correlated with the Northness Index. *Adenostyles* type was positively correlated with pH, rock fragment content, Leptosols, slope and elevation.

Table 6 CCA analysis of plant communities in relation to the considered soil properties (0–20 cm layer) and types, and environmental variables

CCA/variables		Slope	$SOCstock_{1-2}$	Elev	Soil thickness	$SOC_{stockOL}$	Eastness	LP	Northness	PZ	pH_{1-2}	CN_{1-2}	RF_{1-2}	UM	WFPS
Total	LambdaA	0.69	0.58	0.34	0.17	0.14	0.14	0.09	0.09	0.08	0.07	0.07	0.04	0.04	0.04
	F	13.34	13.12	8.41	4.38	3.87	3.93	2.76	2.48	2.35	2.41	2.02	1.29	1.31	1.33
	p value	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.004	0.005	0.003	0.018	0.169	0.162	0.144
	Axes				1	2	3	4	Tot inertia						
	Eigenvalues:				0.781	0.750	0.488	0.184	4464						
	Species–environment correlations:				30.3	59.3	78.2	85.3							

CCA/Variables		Soil thickness	PZ	pH_{1-2}	$SOC_{stockOL}$	LP	CN_{1-2}	$SOCstock_{1-2}$	RF_{1-2}	UM	WFPS
Partial	LambdaA	0.20	0.17	0.10	0.07	0.07	0.06	0.05	0.04	0.04	0.05
	F	5.31	4.94	2.93	2.20	1.99	1.98	1.74	1.29	1.31	1.33
	p value	0.000	0.000	0.001	0.007	0.013	0.014	0.033	0.161	0.166	0.146
	Axes	1			2	3		4	Tot inertia		
	Eigenvalues:	0.311			0.233	0.077		0.062	4464		
	Species–environment correlations:	36.8			64.3	73.4		80.7			

For abbreviations of the variables, refer to Table 1

In the model considering the covariates (Fig. 4b), the highest levels of LambdaA score (above 0.15) were: soil thickness (0.20) and Podzol (0.17). Soil thickness was positively correlated with *Festuca* and *Nardus* types and negatively correlated with *Adenostyles* type.

Considering the first two CCA axes, the different types of vegetation were closer together and overlapped, and they were distinguished primarily by the properties of the soils with which they were associated.

Discussion

Factors affecting SOC stock

Although the investigated alpine soils had limited thicknesses and a high rock fragment content, the average SOC stock down to a depth of 40 cm was 11.72 ± 8.97 kg m^{-2}, higher than that found in the acidophilous grasslands (6.29 ± 2.31 kg m^{-2}) of Gran Paradiso National Park (Italy; Canedoli et al. 2020).

The wide range of SOC stock variation is in part evidence of the effect of soil type: the highest average SOC was found in more developed soils, such as Umbrisols and Podzols, while Leptosols and Fluvisols showed low storage capacity because of their low pedogenetic development and the frequent disturbances (snow erosion, water erosion and burying) to which they are subjected due to their location on the slope. This is in line with some studies (Munoz-Rojas et al. 2012; Wiesmeier et al. 2015) that have examined the impact of land use on SOC stock and have also demonstrated the influence of soil development.

SOC values in the first 10 cm (5.2 ± 2.6 kg m^{-2}) were comparable to those found in a sinkhole with highly heterogeneous soil and vegetation types in the upper Valchiavenna (Lombardy, Italy), at a height of about 1900 m, ranging between 3.3 and 6.5 kg m^{-2} (Ferré et al. 2020).

A declining trend with depth was observed, in line with previous studies (Mendoza-Vega et al. 2003; Munoz-Rojas et al. 2012); 74% of the SOC stock was sequestered in the upper 0–20 cm layer, while the remaining, equal to 3.0 kg m^{-2}, was stored in the 20–40 cm layer, where rock fragments occupied about half of the soil volume. Below 40 cm depth, the rock fragments predominated, resulting in a negligible carbon stock.

Vegetation type was undoubtedly the factor that most influenced the topsoil organic carbon differentiating stocks, vertical distribution, and quality.

The vegetation types differentiated the organic horizons, with the *Rhododendron* type and *Festuca* stocking more SOC (0.18 kg m^{-2} and 0.26 kg m^{-2}, respectively) than the other vegetation types. Both had thick litter layers with high CN_{OL} (30.2 and 47.2 for the *Rhododendron* type and
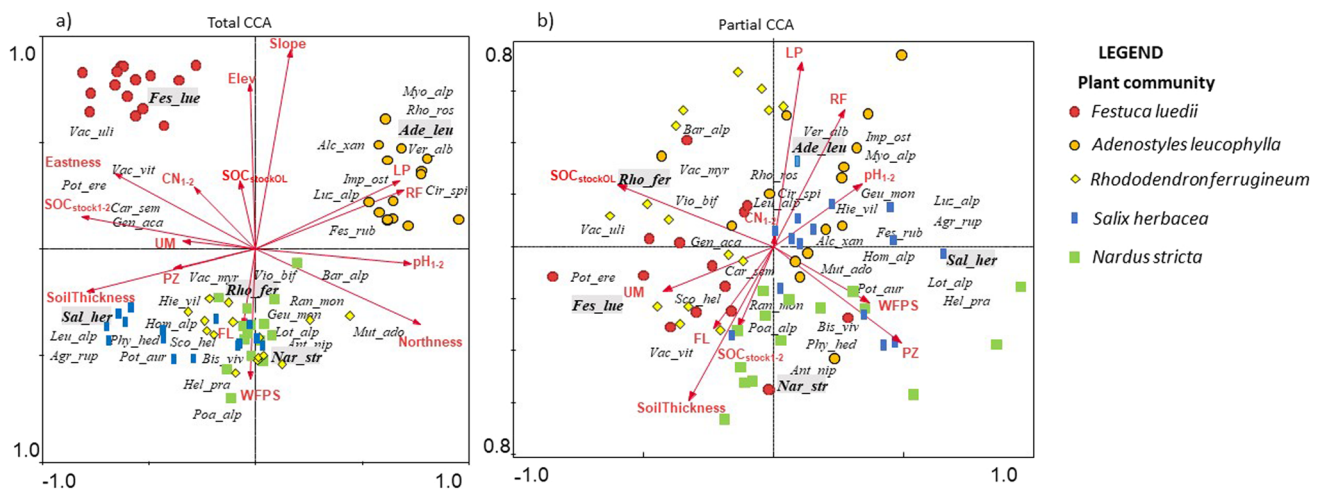
Fig. 4 CCA analysis of plant communities in relation to **a** the considered soil properties (0–20 cm layer) and types and environmental variables **b** with topographic variables as covariates. For abbreviations of the variables, refer to Table 1. *Ade_leu: Adenostyles leucophylla*; *Agr_rup: Agrostis rupestris* All.; *Alc_xan:: Alchemilla xanthochlora* Rothm.; *Ant_nip: Anthoxanthum nipponicum* Honda; *Bar_alp: Bartsia alpina* L.; *Bis_viv: Bistorta vivipara*; *Car_sem: Carex sempervirens*; *Cir_spi: Cirsium spinosissimum* (L.) Scop.; *Fes_lue: Festuca luedii*; *Fes_rub: Festuca rubra* L.; *Gen_aca: Gentiana acaulis* L.; *Geu_mon: Geum montanum* L.; *Hel_pra: Helictochloa praetutiana* (Parl. ex Arcang.) Bartolucci, F.Conti, Peruzzi & Banfi; *Hie_vil: Hieracium villosum* Jacq.; *Hom_alp: Homogyne alpina* (L.) Cass.;

Imp_ost: *Imperatoria ostruthium*; *Sco_hel: Scorzoneroides helvetica*; Leu_alp: *Leucanthemopsis alpina*; Lot_alp: *Lotus corniculatus* L. subsp. *alpinus* (DC.) Rothm.; *Luz_alp: Luzula alpinopilosa* (Chaix) Breistr.; *Mut_ado*: *Mutellina adonidifolia*; *Myo_alp: Myosotis alpestris* F.W.Schmidt; *Nar_str*: *Nardus stricta*; *Phy_hed: Phyteuma hedraianthifolium* Rich.Schulz; *Poa_alp: Poa alpina* L.; *Pot_aur: Potentilla aurea*; *Pot_ere: Potentilla erecta* (L.) Raeusch.; *Ran_mon*: *Ranunculus montanus* Willd.; *Rho_fer: Rhododendron ferrugineum*; *Rho_ros: Rhodiola rosea* L.; *Sal_her: Salix herbacea*; *Vac_myr: Vaccinium myrtillus*; *Vac_uli: Vaccinium uliginosum*; *Ver_alb: Veratrum album* L.; *Vac_vit: Vaccinium vitis-idaea* L.; *Vio_bif: Viola biflora* L

Festuca), indicating a slowdown in organic matter decomposition (Hobbie 2015; Steffen et al. 2007). In contrast, the organic horizons of *Salix* and *Nardus* were thinner or absent.

Regardless of the soil type, *Festuca* appears to contribute to SOC enrichment in the 20-cm topsoil. This is likely because of its high (above- and belowground) biomass, which is promoted by the high solar radiation on the SE-facing slope and SOM quality. From high values in the OL layer, the C:N ratio in the mineral soil decreased, but still remained quite high, indicating a type of SOM that is more resistant to mineralisation.

In terms of topsoil, SOC accumulation under the *Salix* vegetation was comparable to that under the *Festuca* type. The complex process of plant litter decomposition is regulated by the quality of the litter, but also by pedoclimatic factors (Coûteaux et al. 1995; Santa Regina and Tarazona 2001). In this regard, the *Salix* type is the typical vegetation of the nival valleys, where the snow cover persists for many months and moisture levels are high even in the absence of snow cover; this may have slowed down the SOC mineralization by limiting microbial activity due to the lack of oxygen and the lower temperatures caused by the higher soil water content. *Salix* had the lowest ratio of aboveground to belowground biomass. Previous authors have reported that in plants found in tundra ecosystems (in our case, alpine tundra), the belowground biomass is

much higher than the aboveground biomass. Particularly, fine roots, rhizomes and belowground stems are present in a shallow layer of organic matter at the soil surface. This material accumulates because of reduced decomposition rates in cold, and sometimes saturated, soils (Iversen et al. 2015). This imbalance can be attributed to a different phenological development between above- and belowground parts in most tundra species, where a longer growing season (up to about 50%) can be observed in the belowground apparatus than aboveground (Blume-Werry et al. 2016).

Soils under *Adenostyle*s had the lowest SOC stocks (3.1 kg m^{-2}) in the 0–20 cm layer. In this regard, although *Adenostyles* had almost twice the belowground biomass of the other vegetation types, it had a significant fraction of coarse and fine roots with lower turnover rates than very fine roots (Schneider et al. 2006). This suggests that, in addition to a SOC loss through erosion, due to the distribution of this vegetation on steep slopes, the scarcity of SOC compared to the other vegetation types may also be due to the characteristics of the organic matter inputs. As a further confirmation of this, based on the C:N values obtained, which are strictly related to the rate of SOM decomposition (Newbery and Gartlan 1996; Hodge et al. 1998), the fine roots of *Adenostyles* showed lower degradation rates than the other plant types studied.

Topographic and geomorphological factors were mainly found to indirectly influence the SOC stock, and directly act as discriminator of the plant community, similar to the findings of Zhu et al. (2019). In our study area, elevation, aspect and slope were determinants in shaping the spatial patterns of the plant types: *Salix*, *Rhododendron* and *Nardus* types were mostly found on the valley floor or connecting the valley floor and slopes, with a low slope gradient. *Festuca* and *Adenostyles* were mainly found at higher elevations on steep slopes, the former on the south-facing slope and the latter on the more rocky north-facing slope.

Despite the limited altitudinal range, the SOC stock increased with elevation, confirming what other authors have observed (Leifeld et al. 2009; Zhang et al. 2021). This in addition to the direct effect that elevation has on stock variability by affecting plant distributions, as in the case of *Festuca,* where soils had the highest observed SOC stock.

Hypotheses on the effects of climate change

Alpine ecosystems above treelines are particularly prone to global warming, since they are characterised by low temperatures (Körner 2003).

The SOC balance could be affected by the increase in temperature, which would lead to a change in the composition and extension of the plant community, altering the quality and quantity of organic matter input to the soil or the composition and activity of microbial communities, thus changing the C utilisation efficiency of soil microorganisms and the losses through mineralisation (Allison et al. 2010; Schindlbacher et al. 2011; Manzoni et al. 2012).

Long-term monitoring of vegetation in alpine environments indicates that rising temperatures observed over the last century have influenced the range and ecology of plant species (Parolo and Rossi 2008). In particular, alpine plants may respond to the rising temperatures predicted in the IPCC report (IPCC 2021) either by adapting their life cycles to the new environmental conditions or shifting their distribution range upwards. Particularly at higher elevations above the current tree line, shrub species (such as *Rhododendron ferrugineum*) are expected to expand as glaciers retreat (Gentili et al. 2020). Cannone et al. (2007), in their work on the upward shift of alpine vegetation due to climate change during the period 1953–2003, observed a marked increase in shrubs (*Rhododendron ferrugineum* and *Kalmia procumbens* (L.) Gift, Kron & Stevens ex Galasso, Banfi & F.Conti), at the expense of alpine grasslands. In the alpine belts, the abandonment of pastures has also led in the recent past and continues to lead to the recovery of *Rhododendron ferrugineum* shrublands (especially on northern and eastern aspects or in moist sites), confirming the great vitality and competitiveness of this community (Lasen 2017; Francon et al. 2021). Therefore, from the subalpine to the alpine belt, *Rhododendron ferrugineum* is a dominant shrub species functioning as an ecological indicator of the response of alpine ecosystems to global warming (Francon et al. 2020). In addition, in our study area, *Rhododendron ferrugineum* was abundant and had expanded over the last 20 years (observing the orthophotos) and it is expected to continue to expand in the short to medium term replacing other plant communities, such as *Salix herbacea,* associated with prolonged snow cover and relatively lower temperatures*,* first resulting in a decline in biodiversity.

The change in vegetation following the rise in temperature would also have an impact on the SOC stock of the investigated soils. The expansion of the *Rhododendron* type would imply a change in the quantity and quality of organic inputs; the results showed that its litter was among the most recalcitrant, thicker, and slower to decompose and transform into stable humus than that of the vegetation types that it would replace. Although we lack data on the *Rhododendron* roots, we can hypothesize a decrease in SOC input of hypogean origin in the short to medium term based on evidence that the mass of roots less than 2 mm in diameter, which have a higher turnover rate than other size classes (Schneider et al. 2006), is lower in shrubs than in herbaceous species (Pornaro et al. 2017).

The SOC stock balance is determined by organic carbon gains through litter and plant roots (Smith 2008), but also by losses due to mineralisation. In this regard, several field and laboratory warming experiments and observational studies across climatic gradients have largely shown that warming increases the rate of SOC decomposition to CO_2 (Melillo et al. 2002; Conant et al. 2011), because it stimulates microorganism activity (Kirschbaum 2006).

As a result, it is expected that global warming will result in an increase in SOC loss in the investigated valley in the near future, due to enhanced SOC mineralization but also to a lower input of organic carbon due to the likely vegetation shift toward species with more recalcitrant organic matter, leading to a positive impact of soil carbon feedback on climate change.

Conclusion

We studied the soils of the upper Adamé Valley by investigating the relationships between SOC stocks and topographic factors, soil characteristics and vegetation communities.

The study improved our knowledge of alpine soils and their important role as sinks of SOC stocks. First, it revealed the importance of soil development in the differentiation of SOC stocks; topographic factors had mostly an indirect effect on SOC stocks, affecting the vegetation types that essentially determine the SOC spatial variability, quantity, and quality.

Based on the results, it can be hypothesized that soils will lose OC in the short to medium term in response to rising temperatures, and shorter snow permanence times, reducing the effectiveness of the climate regulation service they provide.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

References

Allison SD, Wallenstein MD, Bradford MA (2010) Soil-carbon response to warming dependent on microbial physiology. Nat Geosci 3:336–340. https://doi.org/10.1038/ngeo846

Baroni C, Martino S, Salvatore MC et al (2014) Thermomechanical stress–strain numerical modelling of deglaciation since the Last Glacial Maximum in the Adamello Group (Rhaetian Alps, Italy). Geomorphology 226:278–299. https://doi.org/10.1016/j.geomorph.2014.08.013

Baroni C, Armiraglio S, Gentili R, Carton A (2007) Landform–vegetation units for investigating the dynamics and geomorphologic evolution of alpine composite debris cones (Valle dell'Avio, Adamello Group, Italy). Geomorphology 84:59–79. https://doi.org/10.1016/j.geomorph.2006.07.002

Bartolucci F, Peruzzi L, Galasso G et al (2018) An updated checklist of the vascular flora native to Italy. Plant Biosyst 152:179–303. https://doi.org/10.1080/11263504.2017.1419996

Batjes NH (2016) Harmonized soil property values for broad-scale modelling (WISE30sec) with estimates of global soil carbon stocks. Geoderma 269:61–68. https://doi.org/10.1016/j.geoderma.2016.01.034

Bhattacharya SS, Kim KH, Das S et al (2016) A review on the role of organic inputs in maintaining the soil carbon pool of the terrestrial ecosystem. J Environ Manag 167:214–227

Blume-Werry G, Wilson SD, Kreyling J, Milbau A (2016) The hidden season: growing season is 50% longer below than above ground along an arctic elevation gradient. New Phytol 209:978–986. https://doi.org/10.1111/nph.13655

Callegari E, Dal Piaz G (1973) Field relationships between the main igneous masses of the Adamello intrusive massif (Northern Italy). Società cooperativa tipografica

Canedoli C, Ferrè C, Abu El Khair D et al (2020) Evaluation of ecosystem services in a protected mountain area: soil organic carbon stock and biodiversity in alpine forests and grasslands. Ecosyst Serv 44:101135. https://doi.org/10.1016/j.ecoser.2020.101135

Cannone N, Sgorbati S, Guglielmin M (2007) Unexpected impacts of climate change onalpine vegetation. Front Ecol Environ 5(7):360–364. https://doi.org/10.1890/1540-9295(2007)5[360:UIOCCO]2.0.CO;2

Ceriani M, Carelli M (1999) Carta delle precipitazioni medie, massime e minime annue del territorio alpino della regione lombardia (registrate nel periodo 1891–1990). Regione Lombardia

Chen Y, Feng J, Yuan X, Zhu B (2020) Effects of warming on carbon and nitrogen cycling in alpine grassland ecosystems on the Tibetan Plateau: a meta-analysis. Geoderma. https://doi.org/10.1016/j.geoderma.2020.114363

Choudhury BU, Fiyaz AR, Mohapatra KP, Ngachan S (2016) Impact of land uses, agrophysical variables and altitudinal gradient on soil organic carbon concentration of North-Eastern Himalayan Region of India. Land Degrad Dev 27:1163–1174. https://doi.org/10.1002/ldr.2338

Conant RT, Ryan MG, Ågren GI et al (2011) Temperature and soil organic matter decomposition rates—synthesis of current knowledge and a way forward. Glob Chang Biol 17:3392–3404. https://doi.org/10.1111/j.1365-2486.2011.02496.x

Conforti M, Lucà F, Scarciglia F et al (2016) Soil carbon stock in relation to soil properties and landscape position in a forest ecosystem of southern Italy (Calabria region). Catena (amst) 144:23–33. https://doi.org/10.1016/j.catena.2016.04.023

Coûteaux M-M, Bottner P, Berg B (1995) Litter decomposition, climate and liter quality. Trends Ecol Evol 10:63–66. https://doi.org/10.1016/S0169-5347(00)88978-8

Dorji T, Odeh IOA, Field DJ (2014) Vertical distribution of soil organic carbon density in relation to land use/cover, altitude and slope aspect in the Eastern Himalayas. Land (basel) 3:1232–1250. https://doi.org/10.3390/land3041232

Drewnik M, Musielok Ł, Stolarczyk M et al (2016) Effects of exposure and vegetation type on organic matter stock in the soils of subalpine meadows in the Eastern Carpathians. Catena (amst) 147:167–176. https://doi.org/10.1016/j.catena.2016.07.014

Ferré C, Caccianiga M, Zanzottera M, Comolli R (2020) Soil–plant interactions in a pasture of the Italian Alps. J Plant Interact 15:39–49. https://doi.org/10.1080/17429145.2020.1738570

Francon L, Corona C, Till-Bottraud I et al (2020) Assessing the effects of earlier snow melt-out on alpine shrub growth: the sooner the better? Ecol Indic 115:106455. https://doi.org/10.1016/j.ecolind.2020.106455

Francon L, Corona C, Till-Bottraud I et al (2021) Shrub growth in the Alps diverges from air temperature since the 1990s. Environ Res Lett 16:074026. https://doi.org/10.1088/1748-9326/ac0b67

Garcia-Pausas J, Casals P, Camarero L et al (2007) Soil organic carbon storage in mountain grasslands of the pyrenees: effects of climate and topography. Biogeochemistry 82:279–289. https://doi.org/10.1007/s10533-007-9071-9

Gentili R, Baroni C, Panigada C et al (2020) Glacier shrinkage and slope processes create habitat at high elevation and microrefugia across treeline for alpine plants during warm stages. CATENA 193:104626. https://doi.org/10.1016/j.catena.2020.104626

Hagedorn F, Martin M, Rixen C et al (2010) Short-term responses of ecosystem carbon fluxes to experimental soil warming at the Swiss alpine treeline. Biogeochemistry 97:7–19. https://doi.org/10.1007/s10533-009-9297-9

Hobbie SE (2015) Plant species effects on nutrient cycling: revisiting litter feedbacks. Trends Ecol Evol 30:357–363. https://doi.org/10.1016/j.tree.2015.03.015

Hodge A, Stewart J, Robinson D et al (1998) Root proliferation, soil fauna and plant nitrogen capture from nutrient-rich patches in soil. New Phytol 139:479–494. https://doi.org/10.1046/j.1469-8137.1998.00216.x

Hoffmann U, Hoffmann T, Jurasinski G et al (2014) Assessing the spatial variability of soil organic carbon stocks in an alpine setting (Grindelwald, Swiss Alps). Geoderma 232–234:270–283. https://doi.org/10.1016/j.geoderma.2014.04.038

IPCC (2021) Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change

IUSS Working Group WRB (2022) World reference base for soil resources. International soil classification system for naming soils and creating legends for soil maps, 4th edn. International Union of Soil Sciences (IUSS), Vienna, Austria

Iversen CM, Sloan VL, Sullivan PF et al (2015) The unseen iceberg: plant roots in arctic tundra. New Phytol 205:34–58. https://doi.org/10.1111/nph.13003

Jendoubi D, Liniger H, Speranza CI (2019) Impacts of land use and topography on soil organic carbon in a Mediterranean landscape (north-western Tunisia). Soil 5:239–251. https://doi.org/10.5194/soil-5-239-2019

Jónsson JÖG, Davídsdóttir B (2016) Classification and valuation of soil ecosystem services. Agric Syst 145:24–38

Kirschbaum M (2006) The temperature dependence of organic-matter decomposition—still a topic of debate. Soil Biol Biochem 38:2510–2518. https://doi.org/10.1016/j.soilbio.2006.01.030

Körner C (2003) Alpine plant life. Springer, Berlin

Kumar A, Sharma MP, Taxak AK (2017) Effect of vegetation communities and altitudes on the soil organic carbon stock in Kotli Bhel-1A catchment. India Clean (weinh) 45:1600650. https://doi.org/10.1002/clen.201600650

Kuznetsova AI (2022) Influence of vegetation on soil carbon stocks in forests (review). For Sci Issues 5:1–35. https://doi.org/10.31509/2658-607x-202251-100

Lasen C (2017) Descrizione degli habitat dell'Alto Adige. Provincia Autonoma di Bolzano-Alto Adige, Ripartizione Natura, paesaggio e sviluppo del territorio. https://www.provinz.bz.it/natura-ambiente/natura-territorio/tutela/habitat.asp. Accessed 16 Jan 2023

Leifeld J, Zimmermann M, Fuhrer J, Conene F (2009) Storage and turnover of carbon in grassland soils along an elevation gradient in the Swiss Alps. Glob Change Biol 15:668–679. https://doi.org/10.1111/j.1365-2486.2008.01782.x

Li H, Wu Y, Chen J et al (2021) Responses of soil organic carbon to climate change in the Qilian Mountains and its future projection. J Hydrol (amst). https://doi.org/10.1016/j.jhydrol.2021.126110

Manzoni S, Taylor P, Richter A et al (2012) Environmental and stoichiometric controls on microbial carbon-use efficiency in soils. New Phytol 196:79–91. https://doi.org/10.1111/j.1469-8137.2012.04225.x

Martellos S, Bartolucci F, Conti F et al (2020) FlorItaly—the portal to the Flora of Italy. PhytoKeys 156:55–71. https://doi.org/10.3897/phytokeys.156.54023

Melillo JM, Steudler PA, Aber JD et al (2002) Soil warming and carbon-cycle feedbacks to the climate system. Science (1979) 298:2173–2176. https://doi.org/10.1126/science.1074153

Melillo JM, Frey SD, Deangelis KM et al (2017) Long-term pattern and magnitude of soil carbon feedback to the climate system in a warming world

Mendoza-Vega J, Karltun E, Olsson M (2003) Estimations of amounts of soil organic carbon and fine root carbon in land use and land cover classes, and soil types of Chiapas highlands, Mexico. For Ecol Manag 177:191–206. https://doi.org/10.1016/S0378-1127(02)00439-5

Munoz-Rojas M, Jordan A, Zavala LM et al (2012) Organic carbon stocks in Mediterranean soil types under different land uses (Southern Spain). Solid Earth 3:375–386. https://doi.org/10.5194/se-3-375-2012

Newbery DMcC, Gartlan JS (1996) A structural analysis of rain forest at Korup and Douala-Edea, Cameroon. Proc R Soc Edinb Sect B Biol Sci 104:177–224. https://doi.org/10.1017/S0269272700006138

Oueslati I, Allamano P, Bonifacio E, Claps P (2013) Vegetation and topographic control on spatial variability of soil organic carbon. Pedosphere 23:48–58. https://doi.org/10.1016/S1002-0160(12)60079-4

Parolo G, Rossi G (2008) Upward migration of vascular plants following a climate warming trend in the Alps. Basic Appl Ecol 9:100–107. https://doi.org/10.1016/j.baae.2007.01.005

Parras-Alcántara L, Lozano-García B, Galán-Espejo A (2015) Soil organic carbon along an altitudinal gradient in the Despenaperros Natural Park, southern Spain. Solid Earth 6:125–134. https://doi.org/10.5194/se-6-125-2015

Perez-Riverol Y, Kuhn M, Vizcaíno JA et al (2017) Accurate and fast feature selection workflow for high-dimensional omics data. PLoS ONE 12:e0189875. https://doi.org/10.1371/journal.pone.0189875

Pornaro C, Schneider MK, Leinauer B, Macolino S (2017) Above- and belowground patterns in a subalpine grassland-shrub mosaic. Plant Biosyst 151:493–503. https://doi.org/10.1080/11263504.2016.1187679

R Core Team (2022) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.r-project.org/. Accessed 15 Apr 2022

Santa Regina I, Tarazona T (2001) Nutrient pools to the soil through organic matter and throughfall under a Scots pine plantation in the Sierra de la Demanda, Spain. Eur J Soil Biol 37:125–133. https://doi.org/10.1016/S1164-5563(01)01072-X

Sartori G, Mancabelli A, Wolf U (2005) Atlante dei suoli del Parco Adamello-Brenta. Suoli e paesaggi

Scharlemann JPW, Tanner EVJ, Hiederer R, Kapos V (2014) Global soil carbon: understanding and managing the largest terrestrial carbon pool. Carbon Manag 5:81–91

Schindlbacher A, Rodler A, Kuffner M et al (2011) Experimental warming effects on the microbial community of a temperate mountain forest soil. Soil Biol Biochem 43:1417–1425. https://doi.org/10.1016/j.soilbio.2011.03.005

Schneider MK, Lüscher A, Frossard E, Nösberger J (2006) An overlooked carbon source for grassland soils: loss of structural carbon from stubble in response to elevated pCO_2 and nitrogen supply. New Phytol 172:117–126. https://doi.org/10.1111/j.1469-8137.2006.01796.x

Sjögersten S, Alewell C, Cécillon L et al (2011) Mountain soils in a changing climate—vulnerability of carbon stocks and ecosystem feedbacks. In: Soil carbon in sensitive European ecosystems. Wiley, New York, pp 118–148

Smith P (2008) Land use change and soil organic carbon dynamics. Nutr Cycl Agroecosyst 81:169–178. https://doi.org/10.1007/s10705-007-9138-y

Steffen KT, Cajthaml T, Šnajdr J, Baldrian P (2007) Differential degradation of oak (*Quercus petraea*) leaf litter by litter-decomposing basidiomycetes. Res Microbiol 158:447–455. https://doi.org/10.1016/j.resmic.2007.04.002

Streit K, Hagedorn F, Hiltbrunner D et al (2014) Soil warming alters microbial substrate use in alpine soils. Glob Change Biol 20:1327–1338. https://doi.org/10.1111/gcb.12396

ter Braak, Cajo JF, Smilauer P (2002) CANOCO reference manual and CanoDraw for Windows user's guide: software for canonical community ordination (version 4.5)

Wiesmeier M, von Lützow M, Spörlein P et al (2015) Land use effects on organic carbon storage in soils of Bavaria: the importance of soil types. Soil Tillage Res 146:296–302. https://doi.org/10.1016/j.still.2014.10.003

Yimer F, Ledin S, Abdelkadir A (2006) Soil organic carbon and total nitrogen stocks as affected by topographic aspect and vegetation in the Bale Mountains, Ethiopia. Geoderma 135:335–344. https://doi.org/10.1016/j.geoderma.2006.01.005

Yu H, Zha T, Zhang X et al (2020) Spatial distribution of soil organic carbon may be predominantly regulated by topography in a small revegetated watershed. Catena (amst). https://doi.org/10.1016/j.catena.2020.104459

Zhang Y, Ai J, Sun Q et al (2021) Soil organic carbon and total nitrogen stocks as affected by vegetation types and altitude across the mountainous regions in the Yunnan Province, south-western China. Catena (amst). https://doi.org/10.1016/j.catena.2020.104872

Zhao Y, Mou XM, Wei M, Li XG (2021) Effect of vegetation mosaic on spatial heterogeneity of soil organic carbon mineralization and nitrification in an alpine meadow. Appl Soil Ecol. https://doi.org/10.1016/j.apsoil.2021.104007

Zhu M, Feng Q, Qin Y et al (2019) The role of topography in shaping the spatial patterns of soil organic carbon. Catena (amst) 176:296–305. https://doi.org/10.1016/j.catena.2019.01.029