ORIGINAL PAPER

The potential for an old-growth forest to store carbon in the topsoil: A case study at Sasso Fratino, Italy

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Abstract   There is considerable interest devoted to old-growth forests and their capacity to store carbon (C) in biomass and soil. Inventories of C stocks in old-growth forests are carried out worldwide, although there is a lack of information on their actual potential for C sequestration. To further understand this, soil organic carbon (SOC) was measured in one of Italy's best-preserved old-growth forests, the Sasso Fratino Integral Nature Reserve. This reserve is on the World Heritage List along with other ancient beech forests of Europe, and it is virtually untouched due to the steepness of the terrain, even before legal constraints were imposed. Although the sandstone-derived soils are often shallow, they are rich in organic matter. However, no quantification had been carried out. By systematically sampling the topsoil across the forest, we accurately determined the average amount of SOC (62.0 ± 16.9 Mg ha^{-1}) and nitrogen (4.0 ± 1.2 Mg ha^{-1}) in the top 20 cm. Using the CENTURY model, future dynamics of SOC stocks were predicted to 2050 according to two climate scenarios, A1F1 and B2, the first of high concern and the second more optimistic. The model projected an increase of 0.2 and 0.3 Mg ha^{-1} a^{-1} by 2030 under the A1F1 and B2 scenarios, respectively, suggesting that the topsoil in old-growth forests does not reach equilibrium but continues accumulating SOC. However, from 2030 to 2050, a decline in SOC accumulation is predicted, indicating SOC net loss at high altitudes under the worst-case scenario. This study confirms that soils in old-growth forests play a significant role in carbon sequestration. It also suggests that climate change may affect the potential of these forests to store SOC not only in the long term but also in the coming years.

Introduction

"Old-growth" or "primary" forests are generally defined as naturally regenerated forests of native tree species that have not experienced significant disturbance for a long period of time. These forests are highly biodiverse ecosystems that contribute to climate change mitigation by absorbing large amounts of carbon (C) from the atmosphere and storing it in biomass and soil, as well as providing other essential ecosystem services (Wirth et al. 2009). Soils are the largest C reservoir in terrestrial ecosystems (Scharlemann et al. 2014), and those of old-growth forests are among the C richest globally. However, there is a central question that remains open and subject to debate: whether old-growth forests indefinitely continue to be productive and act as C sinks, or if, at some point, they become C sources by emitting more C to the atmosphere through respiration and decomposition than they absorb through photosynthesis (Zhou et al. 2006; Luyssaert

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The online version is available at http://www.springerlink.com.

Corresponding editor: Tao Xu.

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et al. 2008; Nord-Larsen et al. 2019; Gundersen et al. 2021). Although the amount of C stored in many old-growth forests is undoubtedly significant, it remains largely unknown, especially regarding the soil compartment (Clark et al. 2011; Ķēniņa et al. 2018; Di Matteo et al. 2023). Unlike C in biomass, estimating soil organic carbon (SOC) by remote sensing is challenging, because of the interference of vegetation cover and poor ability to investigate soil in depth (Wang et al. 2018; Guo et al. 2019). Therefore, SOC needs to be directly measured on numerous and evenly distributed sampling points. However, this task is particularly difficult in old-growth forests which are often steep and tangled.

Within the European Union (EU), old-growth forests account for only 3% of the total forest area (Barredo et al. 2021). In 2007, and with extensions until 2021, UNESCO included the transnational environmental site known as the "Ancient and primeval beech forests of the Carpathians and other regions of Europe" on the World Heritage List. This designation was primarily based on the exceptional natural value and high biodiversity exhibited by these forests (https://whc.unesco.org/en/list/1133/). Ten of these forests are in Italy, including Sasso Fratino, which was inscribed on the World Heritage List in 2017. Sasso Fratino extends over the steep slopes of the Apennines ridge in the Emilia Romagna region and covers an area of 781 hectares within the core of the Foreste Casentinesi, Monte Falterona and Campigna National Park. Notably, Sasso Fratino is the first nature reserve in Italy designated as "integral", meaning that public access is prohibited. It was established in 1959 to preserve an environment virtually intact because of the lack of major access routes. The vegetation of Sasso Fratino includes beech trees that can reach up to 500 years in age, making it one of the ten oldest deciduous forests in the Northern Hemisphere. Despite its marked importance, this forest has been relatively little studied. Bianchi et al. (2011) investigated forest dynamics and regeneration processes, while more recently Lelli et al. (2021) explored long-term changes in forest cover, structure, alpha, beta, and gamma diversity, as well as ecological groups within the forest. Also the soils of the Sasso Fratino Forest have received limited attention: Olivari (2009) described three scattered soil profiles, while Sabatini et al. (2015) determined some topsoil properties such as texture, pH, organic C, and total N concentration in a 1-ha wide area. Castronovo et al. (2021) focused on characterizing the cultivable and the total bacterial community in a few soil samples from different altitudes, examining their taxonomy, composition, and structure. However, there is still a need for a comprehensive quantification of the C stored in the soil, considering the altitude gradient within the forest and predicting by models the fate of SOC under different climate change scenarios. Indeed, altitude gradients, through changes in temperature, can provide valuable insights into the study of climate change effects, especially concerning the long-term impact on processes affecting ecosystem structure and function (Garten et al. 1999). When examining SOC dynamics along altitude gradients, temperature appears to be the primary controller of SOC stability and other soil characteristics (Garten and Hanson 2006; Seedre et al. 2015). A SOC stock increase according to increasing elevation has been often reported (e.g., Garten et al. 1999; Garten and Hanson 2006; Mayer et al. 2023), a pattern that can be attributed to several factors, including cooler temperatures at higher elevations. Nevertheless, the SOC response to ongoing climate change still partly remains a matter of debate.

In this work, we hypothesize that the topsoil of the Sasso Fratino Forest—which spans a significant altitude gradient from about 600 up to 1500 m a.s.l.—continues to function as a sink for atmospheric CO_2, but the ongoing global warming will reduce its capacity to store SOC. To assess the SOC stock in the top 20 cm of soil and test the working hypothesis, a systematic soil sampling approach was implemented, and SOC future projections were produced using the CENTURY model based on a pair of contrasting IPCC climate scenarios.

Materials and methods

Study area

The Sasso Fratino integral nature reserve is in the Emilia-Romagna region of Italy on the north-eastern flank of the Apennines ridge (43°50′40″ N, 11°48′50″ E). The climate of the area is temperate oceanic according to the Köppen classification system (i.e., *Cfb* type), which means a mild winter, a moderately hot summer and no real dry season. The mean annual precipitation is around 1600 mm, with 140 rainy days per year. The mean annual temperature is 10 °C, the mean of the coldest month is 2 °C and that of the hottest month is 23 °C (Gonnelli and Bottacci 2009). Snow covers the ground for a period of 1–2 months during the winter season, while fog and low clouds, which bring humidity, especially at higher elevation, are frequent also in summer.

The forest extends over a highly uneven terrain, characterized by sharp ridges, steep slopes (Fig. 1) and rocky banks perched on rugged accumulations of collapsed boulders. Flat areas are rare, mostly generated by collapses, and the average slope is 65%. The maximum altitude is 1520 m a.s.l. (Poggio Scali) and the minimum is 650 m a.s.l. (Ponte di Campo alla Sega).

The geological substrate is rather homogeneous and consists of a single formation, the "Marly-arenaceous", formed in a marine basin during the Middle and Upper Miocene. It is an alternation of sandstones, marls, and schistose siltstones and shales, in which the thickness of the arenaceous

Fig. 1 Overall view of the Sasso Fratino integral nature reserve

(feldspathic-micaceous quartz) layers ranges from a few tens of centimetres to more than two meters, while the marls, siltstones and shales layers usually do not exceed a few tens of centimetres. The intercalations of layers with a calcareous-marl composition, more erodible and alterable than the sandstone banks, causes the heads of the latter to protrude progressively until, lacking the support and weakened by the alteration, they break and fall along the steep slopes.

The upper part of the forest (above 1300 m a.s.l.) includes almost exclusively European beech (*Fagus sylvatica* L.), with sporadic presence of sycamore maple (*Acer pseudoplatanus* L.). Between 800 and 1300 m a.s.l. there are mixed woods of beech and silver fir (*Abies alba* Mill.) and other broad-leaved species, such as *A. pseudoplatanus* L., *Acer platanoides* L., *Ulmus glabra* Huds., *Tilia platyphyllos* Scop., *Fraxinus excelsior* L., and some few specimens of *Taxus baccata* L. Below 800 m a.s.l., the mixed forest of beech and silver fir has a more uneven structure than the one above and contains several specimens of *Quercus cerris* L., *Quercus petraea* (Matt.) Liebl., *Quercus pubescens* Willd., *Acer opalus* Mill., *Acer campestre* L., *Sorbus torminalis* (L.) Crantz, *Ostrya carpinifolia* Scop., *Carpinus betulus* L., *Fraxinus ornus* L. and

Corylus avellana L. Trees taller than 40 m and with diameters greater than 1 m are frequent throughout the forest (Bottacci et al. 2007), and the average wood mass amounts to around 500 m³ ha⁻¹, with peaks of 1000 m³ ha⁻¹ in the most fertile areas (Chiesi et al. 2014). Forest regeneration is extensive where solutions of continuity are created by uprooting.

Soil sampling and analysis

Soil sampling was carried out at 32 points on a regular grid of squares with sides measuring 500 m (Fig. 2) and identified in the field using a GPS (Global Positioning System) device. The samples were collected using a steel cylinder with an inner diameter of 4.2 cm and a height of 20 cm (a volume of 276.95 cm³) after removing the litter layer, i.e., the leaves that had fallen the previous year. The litter layer was not considered in this study due to its ephemeral nature and its absence in late summer, the humus being an "active mull".

The samples were oven-dried at 60 °C until constant weight, then sieved to < 2 mm. The > 2 mm fraction (skeleton) was weighted, and its volume determined by immersion in a graduated cylinder. The bulk density of the fine earth (the < 2 mm fraction) was the ratio between the weight and volume differences between the total sample and the skeleton. An aliquot of the fine earth was pulverised in a ball mill and analysed for C and nitrogen (N) by a CHN Analyser (Perkin-Elmer 2400, series 2). The measured C was assumed to be all in organic form since the pH, which ranged between 4 and 6, is incompatible with the presence of carbonates. For each sampled point, the C stock in the top 20 cm of soil was calculated by considering both the C concentration and the bulk density of the fine earth.

Fig. 2 Topographic map of the Sasso Fratino integral nature reserve with a superimposed 500 m grid with sampling points located at the intersections
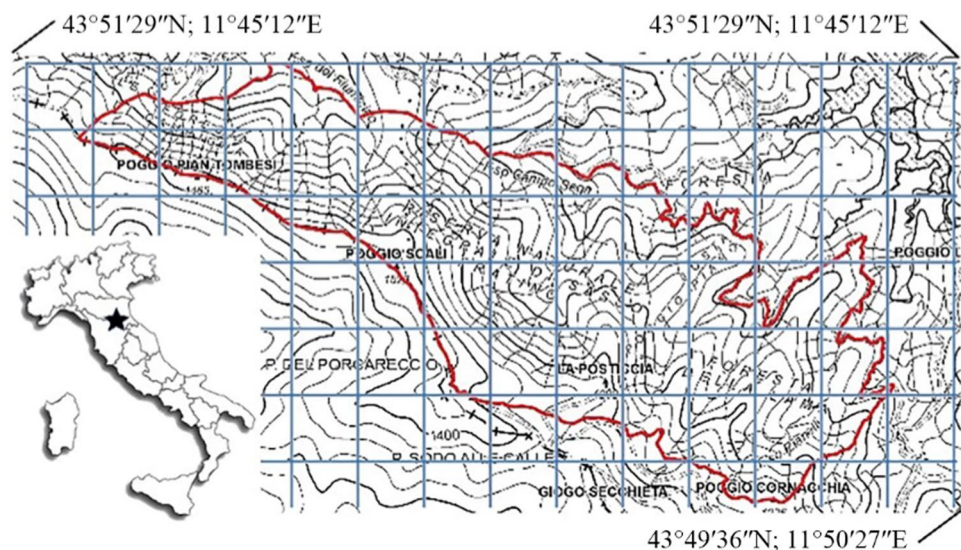
Modelling soil organic carbon stocks

Simulations of SOC dynamics were carried out with version 4.5 of the CENTURY model, which allows for the assessment of C stocks and fluxes through a subdivision into four SOC pools with different decomposition rates (Parton et al. 1987). The model simulates SOC dynamics on a monthly scale, based on maximum and minimum mean temperatures and monthly precipitation. It was originally developed for grasslands but has been successfully applied to various forest types (Kelly et al. 1997), including Mediterranean and Alpine ones (Chiti et al. 2010, 2011).

For simulations of SOC dynamics, CENTURY requires a limited set of input data dealing with climate (e.g., precipitation and temperature), vegetation (e.g., type of forest, type of management) and soil (e.g., particle size distribution, bulk density). The model can simulate past SOC dynamics up to equilibrium in the year selected as year zero of the SOC projections (i.e., 2013 in this study). A model run using CENTURY was done for each of the 32 sampling points using the climatic data recorded by four meteorological stations located on the four different sides of the reserve, all outside although only by a few kilometers: Campigna, Campominacci, La Lama, and Camaldoli. We divided the area of interest into four quadrants, attributing the sample points in climatic terms to the four stations as follows: nine to Campigna, eight to Campominacci, eight to La Lama and seven to Camaldoli. The climate data from the four stations refer to different periods: 1973–2012 for Camaldoli, 1973–2011 for Campigna, 1995–2010 for Campominacci, and 1995–2010 for La Lama. Particle size distribution, used as model input, was determined on four composite samples by combining equal aliquots of fine earth from all points of the same quadrant. This variable was determined by the hydrometer or densimeter method (Gee and Bauder 1986). To initialize the ecosystem status and distribute the total SOC in the different pools considered by the model, a spin-up run for a 5,000 year period was used, after observing that it was the necessary period to equilibrate with the conditions of year zero of the simulation (i.e., 2013), the year of soil sampling. All the model input parameters are noted in Table 1.

Future projections up to 2050 were made based on two climate change scenarios according to the IPCC emission scenarios for the region: A1F1 'world markets-fossil fuel intensive' and B2 'global sustainability' (Nakicenovic et al. 2000). The first, a "most severe" emission scenario, assumes an exponential increase in atmospheric CO_2 up to 970 ppm in 2099, while the latter, a "least severe" scenario assumes a CO_2 concentration reaching 550 ppm in 2099. The projections were performed for each of the 32 sampling points within the forest and grouped according to three elevation classes: $600-900$, 900–1150 and 1150–1500 m a.s.l.

Model evaluation and statistical analysis

Model performance was evaluated by calculating the mean difference between simulated SOC stock at each sampling point and measured data in 2013, namely the root mean square error (RMSE), model efficiency (EF), coefficient of determination (CD) and relative error (E)—as in Eqs. 1–4, respectively—while over- or under-estimation (bias) was evaluated by calculating the mean difference (MD, Eq. 5) between measurements and simulations (Moffat et al. 2007; Smith and Smith 2007):

$$\text{RMSE} = \sqrt{\sum_{(i=1)}^{n} (Pi - Oi)^2 / n} \tag{1}$$

$$\text{EF} = \frac{\sum_{(i=1)}^{n}(Oi - \overline{O})^2 - \sum_{(i=1)}^{n}(Pi - Oi)^2}{\sum_{(i=1)}^{n}(Oi - O)^2} \tag{2}$$

$$\text{CD} = \frac{\sum_{(i=1)}^{n}(Oi - \overline{O})^2}{\sum_{(i=1)}^{n}(Pi - \overline{O})^2} \tag{3}$$

$$\text{E} = \frac{100}{n} \sum_{(i=1)}^{n}(Oi - Pi)/Oi \tag{4}$$

$$\text{MD} = \frac{1}{n} \sum_{(i=1)}^{n}(Pi - Oi) \tag{5}$$

where Pi is the predicted (modelled) data, Oi the observed (measured) data, $\overline{O}$ the average of the observed (measured) data, and n the number of associated values. RMSE and CD vary from 0 to infinity (∞), EF from $-\infty$ to 1, and E

Table 1 Model inputs for simulations of the 32 points using version 4.5 of CENTURY

Quadrant (points)	T. max (°C)	T. min (°C)	Precipitation (mm)	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})
1 [1,2,3,4,5,6,7,8,9]	11.7	5.4	1750.0	360.6	508.4	131.0
2 [10,11,12,13,14,15,16,17]	14.1	7.4	1264.8	542.9	345.6	111.5
3 [19,20,21,22,23,24,26,27]	14.5	7.1	1843.4	433.2	438.7	128.1
4 [18,25,28,29,30,31,32]	15.2	5.4	1240.8	389.1	525	85.9

from $-\infty$ to $+\infty$. For ideal modelling, RMSE and E should be zero, while EF and CD should be one. Note that CD as defined here is not referring to the coefficient of determination (R^2) commonly used in regression analysis.

Differences in C stocks between different elevation classes and the four thermo-pluviometric quadrants were checked using analysis of variance (ANOVA) and the multiple comparisons Tukey's HSD test, both set at $p < 0.05$.

Results

Soil features and SOC stocks

The soils of the Sasso Fratino Forest are rich in both C and N, with mean levels in the top 20 cm of 41.5 ± 21.0 g kg^{-1} (C) and 2.7 ± 1.1 g kg^{-1}(N), respectively. The SOC concentrations were highly variable in each of the three elevation classes, ranging from 25.9 to 83.5 g kg^{-1} (C) in the highest ($1150 - 1500$ m a.s.l.), 17.9 to 69.4 g kg^{-1} (C) in the intermediate ($900 - 1150$ m a.s.l.), and 21.0 to 125.3 in the lowest ($600 - 900$ m a.s.l.) (Table 2; Table S1). Conversely, N concentrations ranged from 1.3 to 6.0 g kg^{-1} (N), 1.3 to 4.3 g kg^{-1} (N), and 0.9 to 4.5 g kg^{-1} (N) in the aforementioned elevation classes, respectively. Overall average C/N ratio was 16.2, which indicates a good degree of humification of soil organic matter, the optimum being between 10 and 20 (Table 2).

Considering the data from all sampling points expressed on a volume basis, i.e., on a per-hectare basis related to the upper 20 cm, the SOC stock was 62.5 ± 17.0 Mg ha^{-1} and the nitrogen 4.0 ± 1.2 Mg ha^{-1}. SOC stock variations in the 32 sample points aligned with the desired accuracy level (tolerable error of 10%). No significant differences were disentangled between the three elevation ranges in terms of both SOC and total N. Similarly, there was not a significant SOC stock variation among the four thermo-pluviometric quadrants in which the area was divided (data not shown).

SOC modelling and future projections

In general, SOC stocks identified from the model were similar to those measured in the field (Fig. 3), which is comforting in terms of efficiency of model application in this environment. Indeed, the model parameters CD (coefficient of determination) and EF (model efficiency) are close to 1, as needed for ideal modelling. The overall C stock derived from the model was lower than the one actually determined by approximately 1.83 Mg ha^{-1} which, however, is an acceptable discrepancy considering the large amount of C involved. The model also succeeded in closely simulating
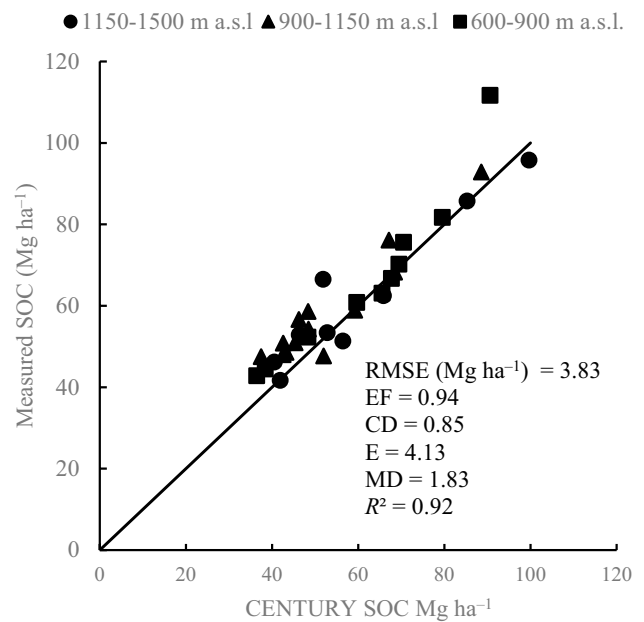

Fig. 3 Measured versus modelled soil organic carbon stocks. Line is the 1:1 relation. The inset reports the statistical performance of the model through root mean square error (RMSE), model efficiency (EF), coefficient of determination (CD), relative error (E), mean difference (MD) and R^2

Table 2 Mean and standard deviation of C and N concentrations in the fine earth (< 2 mm particles), C/N ratio, C and N stocks, rock fragments content and bulk density in the upper 20 cm soil in the Sasso Fratino Forest according to the three elevation classes used for SOC modelling

Elevation classes (m a.s.l)		C (g kg^{-1})	N (g kg^{-1})	C/N	SOC (Mg ha^{-1})	TN (Mg ha^{-1})	Rock frag. (v/v)	Bulk density (Mg m^{-3})
1150–1500	Mean	44.5	2.8	17.4	61.8	3.9	7.0	0.77
	St. dev	16.0	1.3	5.7	17.2	1.6	5.7	0.08
900–1150	Mean	38.8	2.6	15.2	61.6	4.1	6.4	0.90
	St. dev	14.0	1.0	1.7	14.3	1.1	8.0	0.19
600–900	Mean	42.2	2.5	16.3	64.2	4.1	6.8	0.94
	St. dev	28.9	1.0	4.9	18.8	0.9	4.7	0.23
Total Mean		41.5	2.7	16.2	62.5	4.0	6.7	0.88
Total St. dev		21.0	1.1	4.5	17.0	1.2	6.5	0.20

the SOC stock measured separately in the three elevation ranges (Fig. 4).

Future simulations were carried out up to 2050 and divided into two target periods, according to the decarbonization paths indicated by the EU, for which EU climate neutrality should first be approached in 2030 and finally achieved in 2050. The outcomes of these simulations indicated that, with the ongoing climate change, the SOC stock in each of the three elevation ranges will reduce over time under both future scenarios, although with different trends (Fig. 5). In particular, SOC stock will decrease at the highest elevation range until 2050 (Fig. 5a), while it will still increase at the two lower elevations (Fig. 5b, c), at least until 2030, and then slowly decrease until 2050 when it should reach levels similar to those measured in this study. The most severe emission scenario, A1F1, implied lower SOC stocks at any elevation and reference year.

Discussion

SOC stocks

The soils of the Sasso Fratino integral nature reserve are almost unknown except for three profiles described and analysed by Olivari (2009). Two were Cambic Umbrisols according to the WRB classification system (IUSS Working Group WRB 2022), with A-(AB)-B-C sequence of horizons, sandy loam texture, low pH (4.5 − 5.5) and moderate to high cation exchange capacity (20 − 30 cmol (+) kg^{-1}). The third soil was an Eutric Leptosol, with O-A-C sequence of thin horizons, sandy loam texture, moderately low pH (5.5), and very high base saturation. Pedological studies carried out in forests close to Sasso Fratino (Sanesi 1962; Valenti and Sanesi 1967; Sanesi and Certini 2005) generally dealt with Umbric Leptosols or, where the slopes were less pronounced and the soils thicker, with Cambic Umbrisols. In most cases, forest soils of the area have an umbric horizon between 10 and 25 cm in thickness and coinciding with a genetic A horizon, a combination of A1 and A2 horizons or an A horizon with the upper part of a transitional AB horizon (Sanesi and Certini 2005).

The soil C and N concentrations we measured are comparable to those by Sabatini et al. (2015), 37.9 ± 19.2 g kg^{-1} (C) and 3.2 ± 1.6 g kg^{-1} (N) for soil sampled at approximately 1000 m a.s.l. in a small area of the Sasso Fratino Forest. The mean SOC of 62.5 Mg ha^{-1} in the top 20 cm is within the range reported by Harrison et al. (2000) for old-growth beech forests of Europe, i.e., 52 to 84 Mg ha^{-1}.
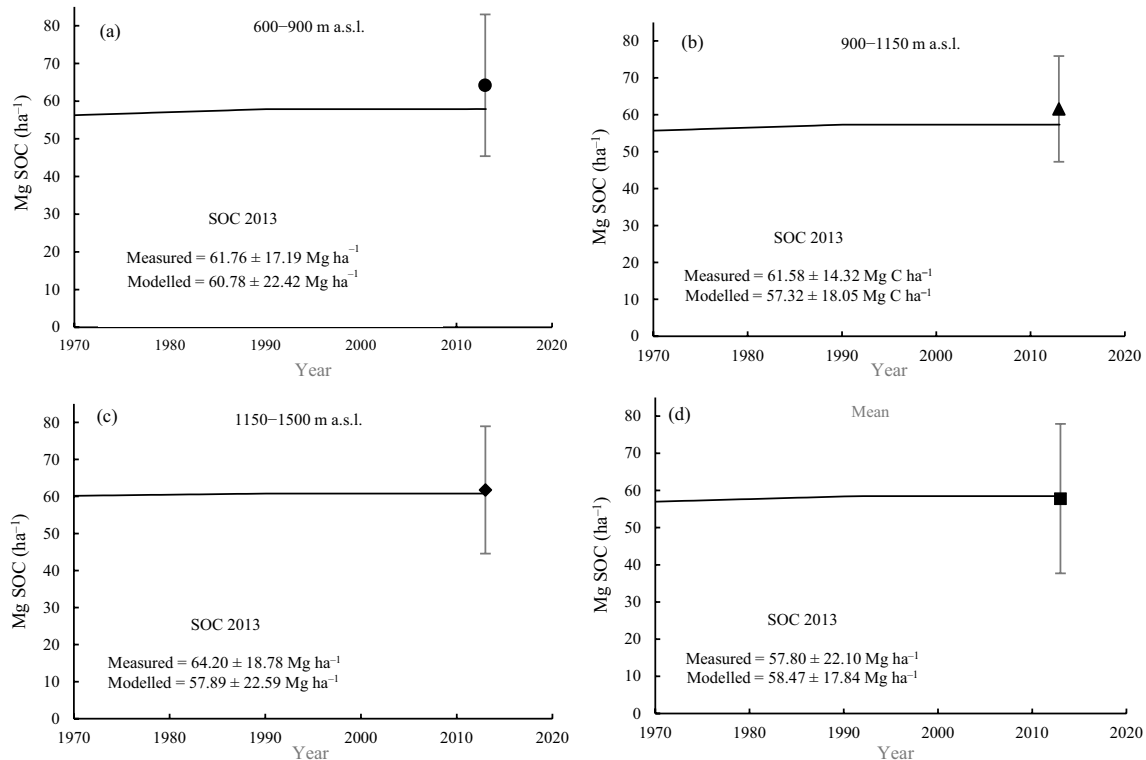

Fig. 4 Best fit between modelled (solid line) and measured (dot) soil organic carbon (SOC) stocks in the top 20 cm of soil in the Sasso Fratino Forest. Bar indicates the standard deviation of the measured SOC stock
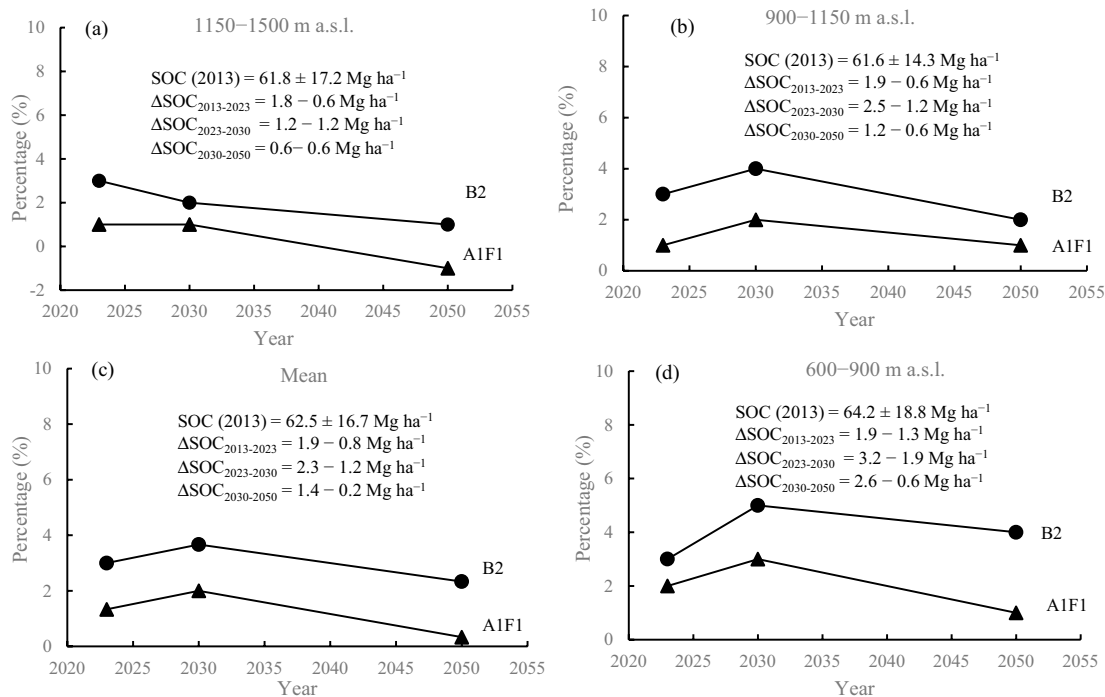
Fig. 5 Percentage variation in soil organic carbon (SOC) stock compared to the reference year 2013 in the entire forest and in each of the three elevation ranges considered, according to the climate change scenarios A1F1 and B2

Considering its entire area (764.2 ha), the Sasso Fratino Forest stored 47.8 Gg C in the top 20 cm of soil. Since most of this soil is on steep surfaces ($40\% - 80\%$ slopes), thus prone to erosion in case of physical disturbances, the current prohibition of management and access to the reserve appears fundamental to preserve C stocks, as well as the integrity of the forest. The relevance of the topsoil C pool in this forest is well understood, especially if it is compared to two other main C reservoirs, the above ground living biomass and the deadwood, which amounted to 382 and 22 Mg ha^{-1}, respectively (Lombardi et al. 2010).

The homogeneous distribution of the sampling points over the reserve allowed for the study of the SOC dynamics in relation to a crucial factor in climate change studies, the variation with altitude. Despite an increase in SOC levels or stock according to altitude reported in several studies (Garten et al. 1999; Rodeghiero and Cescatti 2005; Tian et al. 2016; Yin et al. 2022), we did not find any differences between the three elevation ranges at Sasso Fratino (Table 2). However, there are also studies that showed no significant relationship between SOC and altitude (see Devi 2021) or even, an inverse relationship between the two variables (Seedre et al. 2015; Badía et al. 2016; Bangroo et al. 2017). A possible explanation for the situation described could be related to a decrease in gross primary production (GPP) with increasing elevation, which was demonstrated in the Sasso Fratino Forest by

Maselli et al. (2014) through analyses of climate data and tree ring-widths.

SOC modelling and projections for the future

The CENTURY model successfully simulated changes in SOC across the three elevation classes (Fig. 4a, b, c). The model fit to measure SOC data was good, with results falling within the uncertainties of the measured C stocks (Fig. 4d). It can be concluded that the model accurately simulated the SOC dynamics at different elevations of the study area.

Considering all sampling points, the projections reveal that SOC increased from 2013 to 2022, and was more pronounced under the B2 scenario (0.2 Mg ha^{-1} a^{-1}) than under the A1F1 (0.1 Mg ha^{-1} a^{-1}). SOC will increase from 2023 to 2030 as well, with sequestration rates up to 0.3 Mg ha^{-1} a^{-1} (B2) and 0.2 Mg ha^{-1} a^{-1} (A1F1). These rates, however modest, support what Zhou et al. (2006) proposed, namely that old-growth forest topsoil does not reach equilibrium but can continue to accumulate SOC, albeit at progressively decreasing rates. They also reported an average increasing SOC rate of 0.6 Mg ha^{-1} a^{-1} for an evergreen broadleaf old-growth forest more than 400 years old in Guangdong Province, China. The SOC accumulation rate predicted by the CENTURY model for Sasso Fratino is noteworthy, considering that it is only slightly less than 0.4 Mg ha^{-1} a^{-1} found by both Grüneberg et al. (2014) as the average of 1800

forest plots scattered throughout Germany and surveyed in the context of the National Forest Soil Inventory (NFSI), and by Chiti et al. (2011) in a young oak forest planted on mine spoils at the early stages of pedogenesis, particularly suitable for absorbing C. Nevertheless, the model also revealed that, in the Sasso Fratino old-growth forest, soil as a carbon sink is limited. In particular, soil of the highest elevation $(1150 - 1500$ m) was more susceptible to C loss as CO_2 because of climate change—as reported by Badraghi et al. (2021) in a gradient on the Alps, so much as to become a C source in the worst-case scenario (A1F1) in 2050. Such loss at high altitudes would be somehow counterbalanced by SOC accumulated in the middle and lower elevation ranges where SOC sequestration rates are expected to decline after 2030.

Conclusions

The survey conducted in the Sasso Fratino Forest determined topsoil C and N stocks, both of which are substantial and in line with those of other old-growth forests of Europe. Simulations of the CENTURY model, made according to two future extreme climate change scenarios, showed that there will be a generalized minor increase in SOC in this forest until 2030 and then a decline. This study supports that: (a) soils in old-growth forests play a significant role in carbon sequestration and must be carefully surveyed in C balances and assessments of climate change mitigation; (b) climate change will affect the potential of old-growth forests to store SOC not only in the long-term but in the next few years.

In conclusion, studying and monitoring old-growth forests and their soils are crucial to understanding their dynamics in relation to ongoing climate change.

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