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Drivers of mountain soil organic carbon stock dynamics: A review

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Abstract

Purpose Mountains have unique microclimates and rich plant diversity, resulting in different patterns and dynamics of soil organic carbon (SOC) across plant communities and elevations. Nevertheless, few studies have systematically reviewed the drivers of the dynamics of global SOC in mountainous regions.

Materials and method Here, we collected relevant published literature to analyze the main drivers of the dynamics of global SOC at different elevations and plant communities. Specifically, we analyzed the impact of natural variability and human activity on SOC.

Results and discussion We found that natural factors mainly included climate change, plant succession, and wildfires. Anthropogenic factors mainly included land use changes and grazing practices. SOC stocks at low elevations were more susceptible to grazing, precipitation, and land use changes. Conversely, higher elevations were more susceptible to warming and plant community succession. Notably, montane forests and permafrost, which are important terrestrial carbon sinks, were more easily regulated by wildfires and climate change. However, grazing had different effects on SOC in montane grasslands.

Conclusions This review highlights the synergy of multiple drivers that should be fully considered when investigating mechanisms underlying montane SOC. We recommend that future work explore the impact of extreme weather events on montane SOC.

Keywords Mountain ecosystem · Soil organic carbon · Drivers · Natural changes · Human activities

1 Introduction

Mountains play an important role in carbon cycling of terrestrial ecosystems. Mountains cover 25% of the world's land area and provide habitat for 33% of the world's terrestrial plant species (Antonelli et al. 2018; Notarnicola 2020). Mountains not only provide ecosystem services, including water supply and food for surrounding and downstream human communities (Gret-Regamey and Weibel 2020; Immerzeel et al. 2020; Korner et al. 2017) but are also important regulators of global climate, carbon, and nitrogen (Payne et al. 2017; Wang et al. 2022b). Differences in elevation and hydrothermal combinations lead to remarkable differences in plant communities (Zhang et al. 2021b), which, in turn, leads to substantial spatial heterogeneity in SOC stocks. Mountain forests and alpine permafrost store large amounts of SOC and are important for reducing atmospheric CO_2 and mitigating climate change (Alekseev and Abakumov 2022; Merabtene et al. 2021). Mountain grasslands are also important carbon sinks, and their carbon stocks are regulated by human activity and climate change (Ingrisch et al. 2018). Mountains are also often biodiversity hotspots, making them ideal regions for investigating global terrestrial soil carbon dynamics.

Climate change may drive mountain soil-carbon dynamics. Alpine regions are one of the most vulnerable to climate change (Seddon et al. 2016). Warming has already caused widespread thawing of permafrost at high elevations. Thawing permafrost causes large amounts of previously stored SOC to be decomposed by microorganisms and released into the atmosphere in the form of CO_2 (Chang et al. 2021, 2022; Fouche et al. 2020; Perez-Mon et al. 2022). Warming

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has accelerated the shift of forests to higher elevations in some mountains worldwide (Jiang et al. 2021a; Lu et al. 2021), which then alters primary productivity. Warming increases the altitudinal range of thermophilic species, while decreasing the altitudinal range of cold-adapted species and increasing alpine species richness (Rumpf et al. 2018; Steinbauer et al. 2018). Warming accelerates the retreat of alpine glaciers, which provides space for encroachment by alpine vegetation (Hohensinner et al. 2021). Thus, in the context of climate change, mountain plant community composition and primary productivity may alter the balance of SOC stocks.

Human activity may counteract the direction of changes in mountain SOC. The rapid development of the urban economy has led to a large number of residents migrating from the surrounding mountains to cities (e.g., western Europe), which is conducive to restoration of natural vegetation on abandoned lands and the invasion of woody plants (Ameztegui et al. 2021; Carboni et al. 2018). Large-scale afforestation is a sustainable method to reduce atmospheric CO_2. Afforestation may increase carbon sinks in mountain vegetation and soils (Li et al. 2018b; Piao et al. 2020). While deforestation increases the area of arable land (e.g., tropical mountains), it also reduces aboveground plant biomass and litter mass (Kindermann et al. 2008). Grazing also alters soil physicochemical properties and litter input, which in turn changes SOC stocks (Conant et al. 2017; Godde et al. 2020).

The main purpose of this review is to analyze the main factors affecting mountain SOC. The study areas of this review include major global mountain systems across different climatic regimes. The study sites were distributed across different elevations and plant communities and contained both natural and human factors. Hence, these results are representative and universal and can help us understand the factors influencing mountain SOC.

2 Geographical distribution of studies

To better understand the factors driving the dynamics of global mountain SOC, we searched the relevant published literature on the Web of Science platform (https://www.webofscience.com/wos/woscc/basic-search) and included three selection criteria: (1) mountain biomes at different elevations were the main research objects, and the scope of the study covered major global mountain systems (e.g., Alps and Tianshan Mountains); (2) changes in SOC were the main research objectives; and (3) findings must encompass the main drivers of SOC dynamics.

A total of 80 published articles met our research criteria. We have summarized the main driving factors affecting mountain SOC, including natural and anthropogenic factors (Fig. 1). Specifically, natural factors mainly include: (1) climate change, (2) succession of plant communities, and (3) wildfires. Human factors included: (1) land-use change and (2) grazing practices. In addition, the study sites included major global mountain systems and continents (except Antarctica), ensuring that these findings are representative and universal.

3 Natural changes

3.1 Climate change

3.1.1 Direct effects of warming

Warming enhanced soil respiration rate (R_s). Mountain SOC stock is the result of the long-term balance between organic carbon input and output, and SOC is eventually released into the atmosphere in the form of CO_2 through soil respiration (Li et al. 2020b). Soil respiration is an important regulator

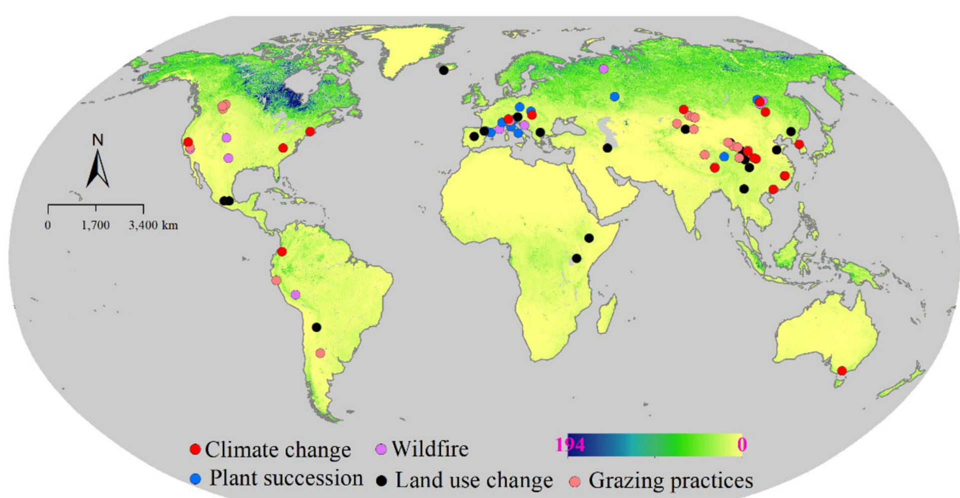

Fig. 1 Geographic distribution of study sites. Dots with different colors represent different driving factors of SOC dynamics. The background map is colored according to global SOC stock (units: kg/m^2) in 0–30 cm depth. SOC stock data from Zenodo (https://zenodo.org/)

of SOC dynamics in terrestrial ecosystems, and abnormal changes in R_s can change the initial stock balance, which in turn leads to an increase or decrease in montane SOC stock (Wang et al. 2019). R_s changes are affected by air temperature, soil moisture, and soil physicochemical properties. Of these, the effect of warming on R_s has received the most attention (Carey et al. 2016; Lei et al. 2021; Nyberg and Hovenden 2020). Anthropogenic climate change has dramatically increased mountain temperatures (Gutierrez-Salazar and Medrano-Vizcaino 2019), and warming enhances R_s at different elevations in mountains, which, in turn, leads to positive feedback between soil respiration and climate warming (Zhang et al. 2015). However, the sensitivity of R_s to warming in different mountain biomes is not uniform, and there are significant differences as a function of elevation.

The loss of SOC in different mountain plant communities is accelerated with increasing temperature. The loss of SOC is not only affected by the magnitude of warming but also regulated by native temperature and initial SOC content. On a regional scale, the Q10 (sensitivity of soil respiration to temperature) of forest soils in cold regions was significantly higher than that in warm regions (Fig. 2a), which may lead to a higher loss of forest SOC in cold regions than in warm regions (Whitby and Madritch 2013; Yang et al. 2022; Zhang et al. 2021a). Additionally, Q10 is positively correlated with initial SOC content, suggesting that warming may lead to higher SOC losses in soils with high initial SOC content (Moriyama et al. 2013; Prietzel et al. 2016). In addition to native temperature and initial SOC content, SOC stock is also affected by differences in elevation and plant community structure and composition. For example, Q10 and R_s increase significantly with elevation (Fig. 2b) (Badraghi et al. 2021; Kong et al. 2022; Li et al. 2017). Nevertheless, there is no consensus on differences in Q10 of different mountain plant communities. Some regional studies have shown that the Q10 of subtropical mountain coniferous and broad-leaved forests are 4.49 and 3.56, respectively, while the Q10 of coniferous and broad-leaved forests in temperate regions are 1.50 and 1.67, respectively (Ma et al. 2019; Zhang et al. 2021a). This difference may be due to differences in native temperature.

Permafrost warming may release more SOC. Low temperatures, humid environments, and acidic soils limit decomposition by microorganisms, which explains why over 50% of global SOC is held in permafrost (Mishra et al. 2021). However, warming causes large amounts of SOC in mountain permafrost to be decomposed and released by microorganisms, which produces a large amount of carbon dioxide and methane, thereby promoting a positive feedback on climate warming and increased soil respiration (Biskaborn et al. 2019; Jin and Ma 2021; Jones et al. 2017; Li et al. 2020a; Yang et al. 2021). It is worth noting that some incubation temperature experiments have shown that Q10 in permafrost regions are also regulated by mineral protection and microbial properties. Specifically, weak organo-mineral associations and high microbial abundance correspond to high Q10 values, whereas high microbial diversity corresponds to low Q10 values (Jiang et al. 2020; Qin et al. 2021; Song et al. 2021). After that, warming alters the microbial community structure of high-elevation lichens and mosses and forms a highly active microbial community that accelerates the decomposition of microbial necromass carbon (a source of SOC), which may temporarily enhance climate warming (Donhauser et al. 2021).

Warming may be a factor causing SOC loss in different mountain plant communities. Elevation causes plant

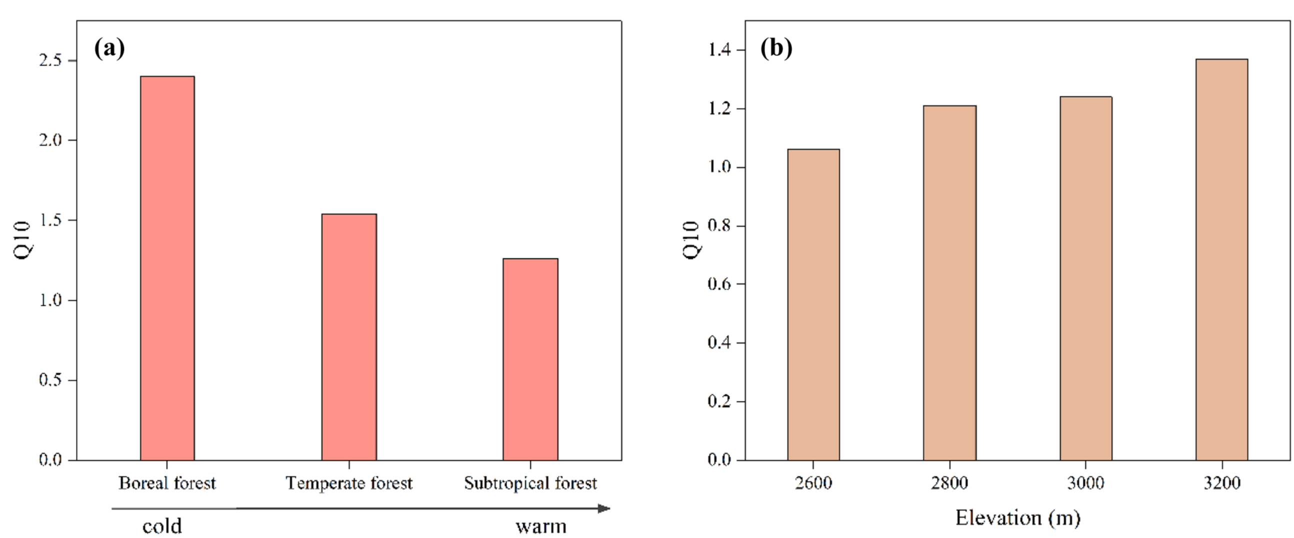

Fig. 2 Sensitivity of soil respiration to temperature (Q10) across different climates and different altitudes. (**a**) Q10 for different forest types (Zhang et al. 2021a), (**b**) Q10 across different altitudes (Kong et al. 2022)

communities to respond differently to changes in SOC decomposition rates. In general, high-elevation plant communities have a higher initial SOC and lower native temperatures, which may lead to a higher rate of SOC loss in these regions than in low-elevation regions.

3.1.2 Precipitation change

Precipitation is also a significant factor affecting the dynamics of SOC stocks. Plant growth, photosynthesis, and NPP (net primary production) are closely related to precipitation (Felton et al. 2021). In addition, changes in precipitation also affect R_s and soil moisture, thereby changing the magnitude and direction of the mineralization rate of SOC (Han et al. 2019; Zhao et al. 2017). In recent decades, regional precipitation has undergone significant changes, and the frequency and intensity of extreme droughts and precipitation have increased significantly, which may alter the accumulation and release of mountain SOC stocks (Guan et al. 2022; Zhang et al. 2022).

Precipitation is the main regulator of organic carbon input and output. Specifically, increased precipitation leads to an increase in aboveground biomass and NPP in dryland, which increases litter inputs and rhizodeposition in dryland soils (Li et al. 2021; Zhang and Xi 2021). In contrast, prolonged drought can result in reduced plant growth or death, resulting in a decline in plant carbon input to soil (Machado-Silva et al. 2021; Nanzad et al. 2021). However, in long-term drought-stressed mountain plant communities (e.g., desert steppe), heavy precipitation alleviates the drought stress of soil microorganisms, and soil microbial activity rapidly increases (within hours or days), thereby rapidly increasing R_s (known as the wetting pulse) (Hou et al. 2021; Jeong et al. 2017; Jiang et al. 2021b; Singh et al. 2021). Additionally, a study in Central European mountains also reported that the SOC content of relatively dry forests (3.28 g·100 g^{-1}) was significantly higher than that of humid forests (1.32 g·100 g^{-1}) when litter input and rhizodeposition changes were stable (Fekete et al. 2021). Furthermore, some subtropical montane forests have also reported short-term declines in SOC content owing to heavy precipitation (Table 1) (Chen et al. 2016b).

Taken together, heavy precipitation increased R_s and reduced SOC content in the short term. However, in the long term, a wetter climate can promote an increase in NPP in dryland, which in turn is conducive to the accumulation of SOC. Furthermore, we suggest that light droughts may increase SOC stocks.

3.2 Succession in plant communities

Economic development and climate change have changed the natural landscape of mountains. Rapid economic development of cities has led to a large number of residents abandoning traditional farming and animal husbandry activities and migrating to cities and towns (Haddaway et al. 2014; MacDonald et al. 2000). The dramatic reduction in mountain population density relieves the pressure of human activity on the local natural environment and promotes the restoration and succession of natural vegetation, which may change prior stocks of SOC (Urbina et al. 2020). Additionally, alpine warming promotes the migration of thermophilic species to higher elevations (e.g., an upward shift of the treeline and meadow), which leads to more complex alpine plant communities and affects SOC (Gatti et al. 2019; Zhang et al. 2021b). Increased warming and decreased human activity may affect the succession of natural vegetation, which may alter the quality and quantity of leaf litter and soil physicochemical properties, thereby changing SOC content.

Table 1 Effects of different precipitation treatments on SOC in subtropical forests (Chen et al. 2016b)

Forest type	Treatment	SOC content ($g·kg^{-1}$)
Broadleaf forest	Double precipitation	25.04
	Natural precipitation	29.06
Mixed forest	Double precipitation	24.99
	Natural precipitation	27.69
Coniferous forest	Double precipitation	16.90
	Natural precipitation	18.99

Long-term succession of plant communities change SOC stocks in low- and mid-elevation mountains. The weakening of agro-pastoral activities promotes secondary succession of natural vegetation on largely abandoned pastures and cultivated lands. In general, succession consists of three stages: (1) the initial stage is dominated by herbaceous vegetation; (2) many shrubs grow during the intermediate stage; and (3) trees become dominant in the final stage (Fino et al. 2020). Increased plant biomass in low- and mid-elevation mountains during long-term succession results in increased surface (0–10 cm) SOC stocks (Fig. 3a), and the SOC stock of secondary forests is slightly higher than that of virgin forests (Fig. 3b) (Lasanta et al. 2020; Sokolowska et al. 2020). However, there may be differences in the magnitude of increases in SOC during the final stages of secondary succession. Regional studies show that SOC stock (0–70 cm) increased more in broadleaf forests (278.55 Mg·ha^{-1}) than coniferous forests (171.55 Mg·ha^{-1}) (Pellis et al. 2019). In addition, the transition from the initial succession stage (Birch forest: 77.69 Mg·ha^{-1}) to the climax succession stage (*Larix gmelinii*: 130.50 Mg·ha^{-1}) significantly increased surface (0–40 cm) SOC stock in secondary forests (Duan et al. 2020). This suggests that succession in secondary forests

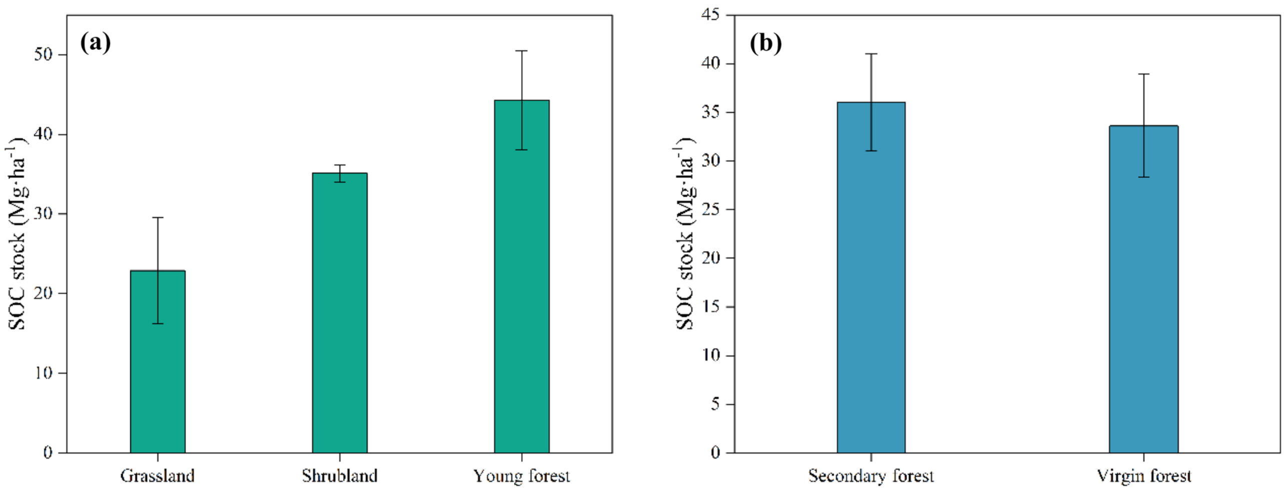

Fig. 3 SOC stocks and standard deviation at different plant successional stages. (**a**) SOC stocks of three succession stages (Lasanta et al. 2020), (**b**) SOC stocks of different forest types (Sokolowska et al. 2020)

(from broad-leaved to coniferous forests) may enhance soil carbon sequestration.

Upward encroachment of low-elevation species alters high-elevation SOC. Climate warming drives forest expansion to higher elevations and increases forest cover in the ecotone between forests and meadows (tundra), which increases aboveground biomass and SOC (Bojko and Kabala 2017; Kammer et al. 2009). However, high-elevation warming leads to the intrusion of alpine grasslands into alpine meadows, which weakens the soil carbon sink capacity (e.g., – 6.0 kg·m^2 in Qinghai-Tibetan Plateau) of alpine meadows (Huang et al. 2022; Liu et al. 2016b). The effect of plant invasion on SOC depends on the productivity of the invasion and the amount of litter input.

Collectively, a secondary succession of abandoned arable land (pasture) may increase SOC, but the magnitude of SOC increase is regulated by plant biomass and litter input in the final succession stage. Succession in secondary forests increases the proportion of litter decomposition products transferred to the soil, which increases forest SOC (Xiong et al. 2020). At high elevations, differences in productivity and biomass between invasive and native species were the main factors influencing the changes in SOC after invasion.

3.3 Wildfire

Warming and drying may increase wildfire frequency and spatial extent. Mountain forests often have relatively thick organic layers that provide abundant fuel for wildfires (Tran et al. 2020). Accordingly, wildfires are regarded as an important factor in forest disturbance (Buma et al. 2020). Heat waves, extreme drought, and the frequent occurrence of dry lightning have increased the frequency and intensity of wildfires, which have burned large areas of forest (e.g., forests in southern Australia) and released large amounts of greenhouse gases (Canadell et al. 2021; Walker et al. 2019). Wildfires also alter physicochemical properties of the topsoil, microbial composition, and amount of litter, which causes changes in SOC (Miesel et al. 2015; Solomun et al. 2021).

Changes in SOC are closely related to the intensity of wildfires. Forest wildfires often result in partial or complete degradation of the organic layer and the formation of a pyrolytic layer containing pyrogenic carbon (Talucci et al. 2020). With gravitational water infiltration, pyrogenic carbon is transferred from the pyrogenic horizon to the mineral soil, which increases the total carbon content of the soil (Reisser et al. 2016). Remarkably, pyrogenic carbon in mineral soils is a stable soil carbon pool owing to its long turnover time (Abney et al. 2019; Santos et al. 2021; Singh et al. 2012). However, different levels of wildfire may lead to an increase or loss of SOC. Specifically, low- to moderate-intensity wildfires increased forest SOC content, but not immediately (Fig. 4a) (Dymov et al. 2021; Gibbon et al. 2010). In general, the surface SOC content may increase after several leaching seasons (Cui et al. 2014). However, a high-intensity wildfire (e.g., > 400 ℃) will significantly reduce the concentration of topsoil SOC (Fig. 4b) (Armas-Herrera et al. 2016; Fultz et al. 2016; Li et al. 2020c), but in years to decades after the fire, SOC will gradually recover owing to plant succession (Dunnette et al. 2014; Guenon et al. 2011). In addition to fire intensity, repeated burning at short intervals also reduces SOC content (Pellegrini et al. 2021).

Low- to moderate-intensity wildfires can increase SOC in montane forests. However, high-intensity and high-frequency fires may accelerate SOC loss. This loss may be temporary because vegetation restoration increases litter input. Pyrogenic carbon from burning vegetation can be stored in mineral soils

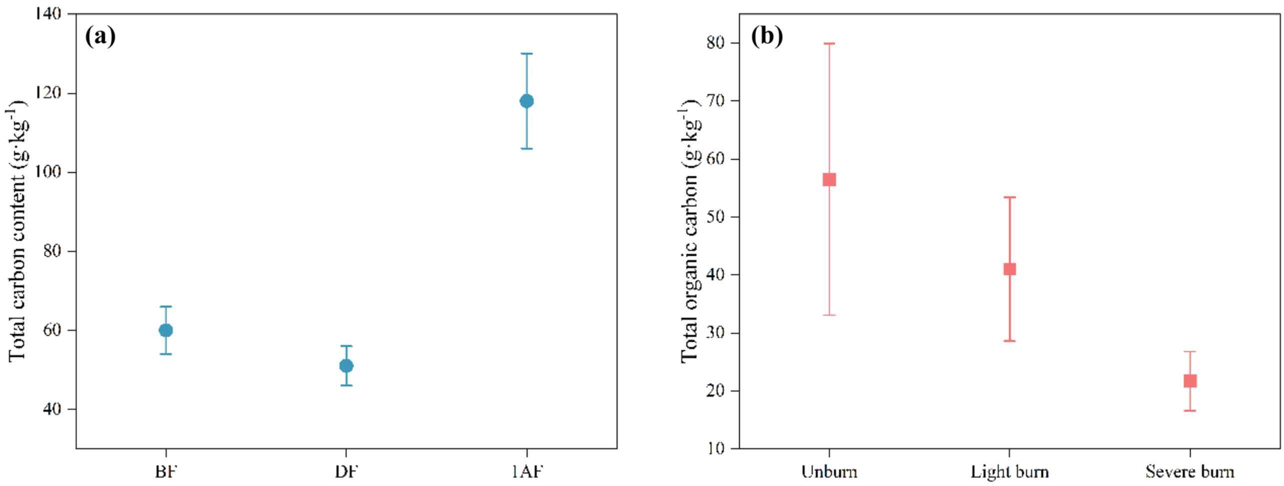

Fig. 4 Mineral SOC content and standard deviation with different burning stages and burning intensity. (**a**) low intensity wildfire and includes three combustion stages: BF (unburnt soil), DF (during fire) and 1AF (one year after fire) (Dymov et al. 2021), (**b**) different burning intensities (Li et al. 2020c)

for thousands of years, and may be an important global carbon sink (Jones et al. 2019).

4 Human activities

4.1 Land use change

Land-use change is a potential factor affecting SOC stocks. Population growth, accompanied by increased food demand, results in the conversion of large amounts of mountain forests and grasslands to arable land and pastures (Zeng et al. 2021). Increased demand for paper, fuel, and building materials has also led to deforestation of large areas of virgin forests (Sandel and Svenning 2013). Human disturbances have disrupted the primary productivity of mountain forests and grasslands, which may weaken the natural carbon sequestration capacity of forest or grassland soils (Santini et al. 2020). Restoration of natural vegetation (e.g., large-scale afforestation) is regarded as an important means of enhancing mountain ecosystem services and carbon sink capacity (Hunziker et al. 2019). Additionally, afforestation can not only change plant community composition and local microclimate, but also increase the yield of plant biomass and litter, which may disrupt the balance of SOC (Hong et al. 2020; Ortiz et al. 2016).

The conversion of forests to croplands and pastures reduces SOC. In some mountainous regions, the expansion of arable land has led to the disappearance of large areas of forest, and deforestation not only reduces aboveground biomass but also changes the physicochemical properties of forest soils, which in turn affects the carbon dynamics of forest soil. (Fujisaki et al. 2015; Tolimir et al. 2020). Specifically, when the forest is converted to cultivated land, the bulk density of the forest soil increases, soil acidity decreases, and litterfall also decreases, which is not conducive to the accumulation of SOC (Fang et al. 2014; Vanacker et al. 2022). Previous studies have reported varying degrees of SOC loss when montane forests were converted to croplands and pastures (Table 2) (Falahatkar et al. 2014; Fusaro et al. 2019; Yimer et al. 2007). Conversely, SOC stocks increased when cropland and grassland were converted to forest (Table 2) (Justine et al. 2020; Zhang et al. 2014).

Afforestation of abandoned croplands and pastures increases SOC. Afforestation increases soil water content and porosity, while decreasing soil bulk density and pH (e.g., input of acidic litter), which favors SOC accumulation (Chen et al. 2016a). Hence, afforestation can increase the carbon storage of mountain ecosystems, which further indicates that afforestation has great potential for reducing atmospheric CO_2 concentrations and alleviating global warming (Bastin et al. 2020). In addition, many afforestation practices globally show that planted forests significantly increase SOC

Table 2 Effects of land use changes on SOC stock

Depth (cm)	Conversion type	SOC stock	References
0–15	Arable land to grassland	+25.0%	Zhang et al. (2014)
0–40	Forest to rangeland	−14.5%	Falahatkar et al. (2014)
0–60	Forest to grassland	−37.7%	Justine et al. (2020)
0–60	Grassland to Forest	+27.4%	
0–100	Forest to arable land	−30.9%	Yimer et al. (2007)
0–100	Grassland to Forest	+50.43%	Zhang et al. (2021c)

stock in abandoned farmland and pastures (Campo et al. 2019; Chiti et al. 2018; Li et al. 2016; Zhang et al. 2021c). However, SOC decreases in early stages and gradually recovers decades later (Li et al. 2015; Menichetti et al. 2017). Different tree species and afforestation methods also affect SOC dynamics. For example, the selection of coniferous species or mixed afforestation can further enhance carbon sequestration capacity (Han et al. 2021; Niu et al. 2015).

Deforestation usually reduces the input of aboveground biomass and litter, thereby resulting in SOC loss. However, afforestation, especially on abandoned farmland and pastures, can improve soil physicochemical properties and increase primary productivity, further enhancing soil carbon sequestration. The increase or loss of SOC caused by land use change is a long-term and slow process. SOC stock changes caused by different land use patterns may take decades or even centuries to reach a new equilibrium (Li et al. 2018a).

4.2 Grazing practices

Grazing is one of the most globally extensive forms of land use and affects SOC in approximately 25% of ecosystems (Chen et al. 2015). Mountain grazing is mainly distributed in montane grasslands and alpine meadows and provides important ecological services, including meat and milk to surrounding low-elevation cities (Xun et al. 2018). Grazing, especially overgrazing, owing to increased human demand for food, has extensive and far-reaching implications for montane ecosystems. Different grazing intensities and patterns change grassland biodiversity, biomass, and soil physicochemical processes, which affect the direction and magnitude of SOC changes (Zhang et al. 2020b). However, the response of SOC to grazing is not immediate and is closely related to additional factors, including elevation, grassland management, and regional climate (Wang et al. 2022c).

The response of SOC to grazing is regulated by several factors. High-intensity grazing reduces primary productivity and aboveground biomass in grasslands, resulting in less litter and SOC stocks (Fig. 5a) (Goenster-Jordan et al. 2021; Vaieretti et al. 2021; Yang et al. 2018; Yuan and Hou 2015; Zhang et al. 2018). In addition to grazing intensity, regional climate differences lead to different responses to grazing. Grazing in warm and humid climates increase SOC, whereas SOC decreases in cold and wet climates (Abdalla et al. 2018). The effects of grazing on SOC in montane grasslands also differ as a function of elevation. The loss of topsoil SOC in low-elevation desert steppe is higher than that in alpine meadow under different grazing intensities, and grazing leads to seasonal changes in SOC concentration in alpine meadows (Norton et al. 2014; Wang et al. 2022a). Grazing also enhances soil respiration, resulting in higher CO_2 effluxes than in ungrazed lands (Gao et al. 2018; Liu et al. 2016a).

Grazing strategies play a key role in the dynamics of grassland carbon stocks. At low and medium intensities of grazing, free grazing reduces plant diversity, soil porosity, and vegetation coverage, thereby reducing SOC and microbial biomass (Lu et al. 2017; Wang et al. 2012; Zhao et al. 2019). However, compared to free grazing, fenced grazing increased above- and below-ground biomass and SOC content at soil depths of 0–100 cm (Fig. 5b) (Bi et al. 2020; Hewins et al. 2018; Zhang et al. 2020a). After that,

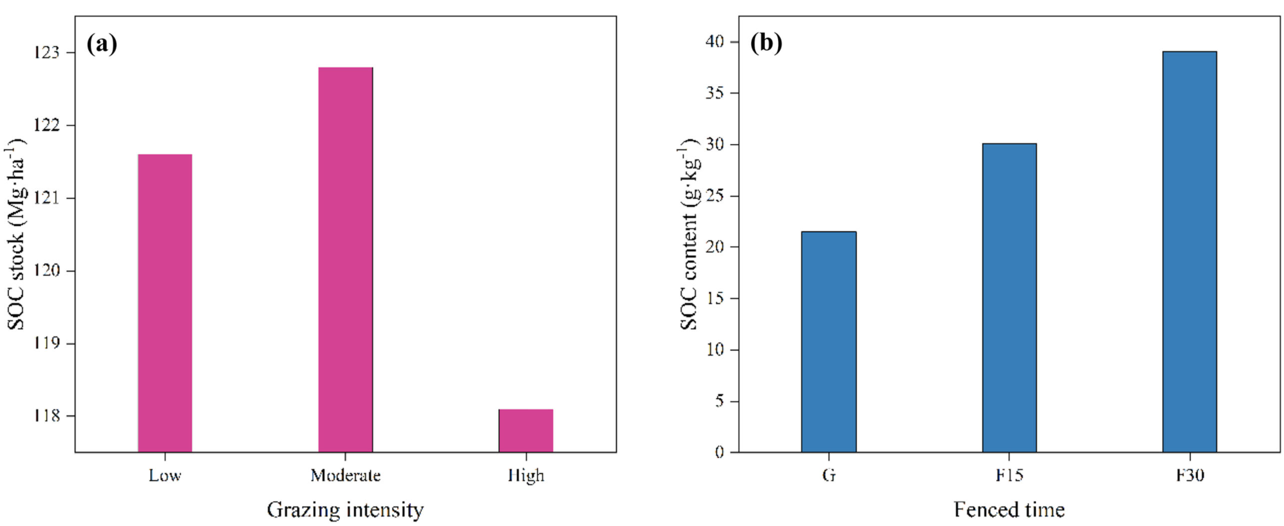

Fig. 5 Effects of grazing intensity and grazing strategy on SOC. (**a**) Effects of different grazing intensities on SOC stocks (Vaieretti et al. 2021), (**b**) effects of grazing strategies on SOC content; G, F15, and F30 represent free grazing, 15 years in fenced, and 30 years in fenced, respectively (Zhang et al. 2020a)

rotational fence grazing can alleviate soil disturbance and increase plant biomass, which can further increase surface SOC (Baronti et al. 2022).

Overall, the dynamics of SOC stocks in montane grasslands are influenced by grazing intensity, regional climate, and grazing management strategies. Differences in the natural environments of different regions lead to more complex responses. Notably, when SOC is regulated by multiple factors, the relative contributions of different factors require further investigation.

5 Summary

In this paper, we reviewed the main factors affecting mountain SOC stock. Mountain SOC dynamics are affected by both natural and anthropogenic factors. Natural factors include climate change, plant community succession, and wildfire. Specifically, warming and heavy precipitation enhance soil respiration rates, which then accelerate the loss of SOC stocks. However, long-term wetting trends increase plant NPP in dryland, which favors SOC accumulation. Furthermore, the magnitude of the increase in soil respiration rate was regulated by the initial SOC, native temperature, elevation, and vegetation type. Plant succession in abandoned cultivated lands or pastures increased SOC content, and the magnitude of the increase was dependent on plant primary productivity at the final succession stage. Warming also caused some plant species to shift upward along elevation gradients and affected SOC in new areas. Moreover, the direction of change in SOC was mediated by differences in productivity between invasive and native species. Mountain forests are also vulnerable to wildfire. High-intensity wildfires reduce forest SOC, whereas moderate- and low-intensity wildfires increase soil total carbon content.

Human factors mainly include land use change and grazing. Specifically, deforestation reduces SOC. In contrast, afforestation of abandoned farmlands and pastures increases the quality and quantity of leaf litter, which increases the SOC stock. Grazing practices can affect SOC in montane grasslands. Notably, differences in climate, elevation, and grazing management strategies alter the direction and magnitude of changes in SOC.

6 Future perspectives

Mountain SOC is affected by both natural and anthropogenic factors. We found that most studies focused on the influence of a single factor on mountain SOC, while ignoring the synergistic effects of multiple factors. It is necessary to quantitatively analyze the relative contributions of multiple factors. Furthermore, studying the future trends of dominant factors is crucial for predicting SOC dynamics in mountain ecosystems.

Anthropogenic climate change has significantly increased the intensity, frequency, and duration of extreme weather and climate events globally (Ummenhofer and Meehl 2017). Extreme weather events can lead to large losses of carbon stocks in terrestrial ecosystems over short periods of time. For example, during the European heatwave in 2003, the loss of soil carbon stocks in Western Europe was equivalent to the amount of carbon sequestered from the atmosphere over three to five years under normal climatic conditions (Vetter et al. 2008). Additionally, extreme precipitation can lead to a large amount of particulate organic carbon entering aquatic ecosystems within a short period of time (Goldsmith et al. 2008). Several studies have reported increasing trends in extreme weather events (e.g., extreme precipitation, heat waves, and extreme wildfires) (Bonekamp et al. 2021; Coop et al. 2022; Nandargi and Dhar 2011; Shi and Durran 2015). Extreme weather or climate events can affect the function and structure of mountain ecosystems, thereby affecting the soil carbon cycle of different plant communities and causing some ecosystems to switch from carbon sinks to carbon sources (Frank et al. 2015). Therefore, understanding the impact of extreme weather and climate events on SOC in mountain ecosystems is critical to improve our ability to predict future changes in mountain SOC stocks.

Author contribution Yong Zhang collected the data and wrote the manuscript. Cheng-bang An directed and reviewed the manuscript. Wen-sheng Zhang and Li-yuan Zheng provided the illustrations and tables. Yan-zhen Zhang and Chao Lu have checked the English grammar of the manuscript. Lu-yu Liu literature download.

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Declarations

Conflict of interest The authors declare no competing interests.

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