8. Mountain soils

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1. Definition and description

Soils can act as relevant carbon (C) reservoirs and/or sinks, as they can store C for variable times, removing it from the atmosphere, thus contributing to the regulation of climate at the planet scale by reducing GHG emissions. Mountain soils in particular can store high amounts of organic C (soil organic C - SOC). Not only the amount of OC stored in soils is important, but also its quality, which in turn affects its persistence (e.g. Cotrufo *et al.,* 2019). In particular, SOC can be retained in different pools such as particulate organic matter and mineral-associated organic matter, which show different turnover rates in soils, depending on soil type and management. These general considerations hold for all soils, but they are particularly relevant in mountain areas where the natural vegetation cover is preserved, soils are mainly undisturbed, and sealing (urbanization) is less pronounced. In such conditions, the organic residues (litter, dead organisms) are not removed from the system, and can enter the carbon cycle by mineralization and humification, and be stored into the soil (mostly as SOC) for long time periods.

The SOC stock is generally defined as the amount of organic C stored in a fixed land surface (e.g., 1 hectare). This amount of SOC refers to a given soil depth (e.g., 30 cm, 1 m) or the whole soil profile, and the input data for the calculation are the soil bulk density (measured in the field or estimated), the stone content (measured or estimated), and the SOC content.

The extent to which this storage function is fulfilled depends on the soil type (and thus on several soil properties such as total depth, organic matter content, texture, aggregation and porosity, humus type), but it is also affected by environmental and site conditions (e.g. climate and slope), land-use and management history (Wiesmeier *et al.*, 2019). In particular, land-use change and soil management practices (e.g., deforestation, overgrazing, tillage practices enhancing erosion) can affect the ability of soils to store carbon, and its residence time in soils.

For this study, the UNEP-WCMC definition of mountains was used, i.e., mountain land is estimated from a digital elevation model based uniquely on elevation (when >2500 m a.s.l.), or a combination of elevation, slope, and local elevation range when < 2 500 m a.s.l. (Kapos, 2000; UNEP-WCMC, 2002). The global mountain area is 39.3 million km^2, or 27 percent of the Earth's land surface (FAO, 2020, forthcoming); of this surface, a large part is covered by forests. According to the Mountain Green Cover Index Data (SDG Indicator 15.4.2), as of 2015 mountain forests covered about 12 924 600 km^2.

Given the extent of mountain forests in the world and their potential for biomass production, it is evident that mountain areas are potentially active as hotspots of SOC stocks, and could stock even more carbon. As underlined by Lehmann *et al.* (2020), a deep understanding of C dynamics in soils is needed to mitigate climate change, but constant care is to be preferred to one-time actions to prevent C emissions into the atmosphere. Mountains and mountain soils are also very vulnerable to climate change, which can increase erosion or enhance the fast mineralization of organic matter due to higher temperatures and modifications in the precipitation regimes (Hock *et al.*, 2019). Detailed inventories of SOC stocks can help to simulate climate and land-use changes, and their consequences on soils (e.g. Shi *et al.*, 2020). Thus, the management of mountain land and soils is a crucial issue in climate change mitigation strategies.

2. Global distribution of hotspot

In Table 33 (Annex 2), we collected relevant literature, focusing on SOC stocks in mountains all over the world (Figure 19). One relevant drawback for comparing the estimations of average SOC stock values in the different mountain ranges is that the authors used a broad variety of methods (Table 33). For example, bulk density can be measured from specific samples or estimated using pedotransfer functions (often leading to an overestimation of bulk density values, and thus of stocks). Moreover, each study considers different soil depths for C stocks calculation: some researchers measure it only in topsoil (generally, 0–10 cm or 0–30 cm), others consider different depths (0–40, 0–50, 0–60 cm, etc.), some divide topsoil from subsoil stocks, others equalize all stocks to 1 m depth, and others calculate it on the whole soil profile (Table 33). When dealing with forest soils, some researchers calculate stocks included in organic horizons, while others neglect this amount. Thus, a precise comparison between SOC stocks between different mountain ranges, dependent on climate and vegetation or land-use differences, is impossible. Only broad differences and relationships with environmental properties can be estimated.

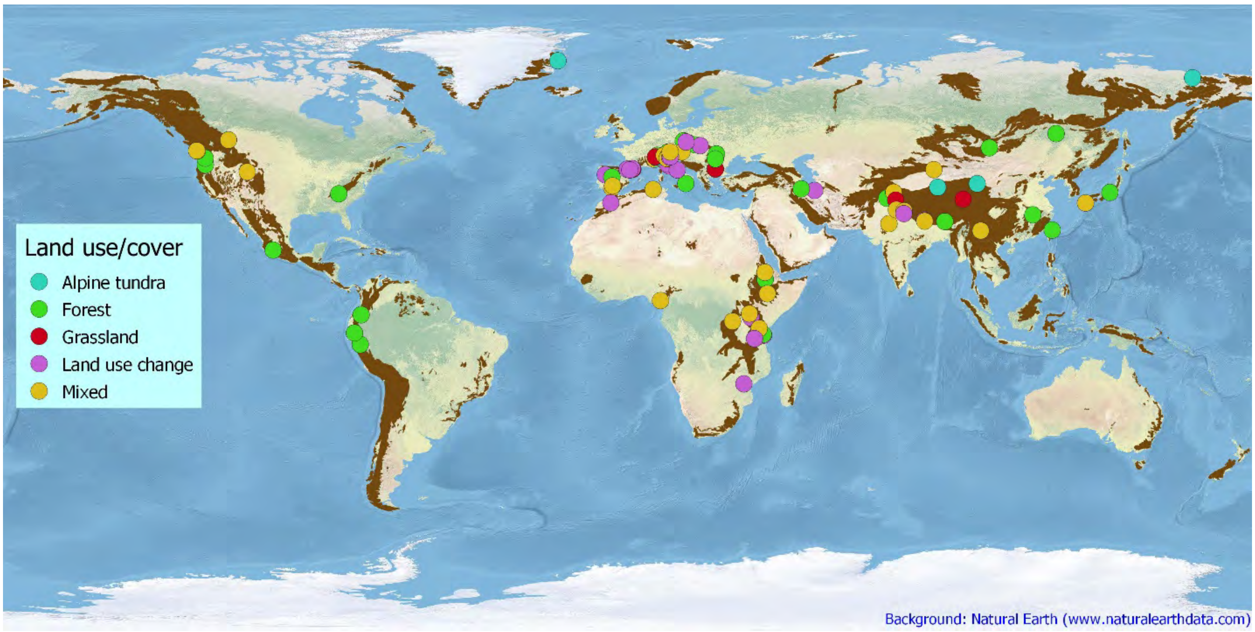

Figure 19. A map showing the localization of the literature data presented in Table 33 (Annex 2)

Shapefiles were produced by the Global Mountain Biodiversity Assessment (GMBA) for the Mountain Portal representing mountain ranges (University of Bern, 2020). The category "Mixed" refers to the presence of more than one land use/cover

3. Global carbon stocks and additional carbon storage potential

As visible in Annex 2, the large variation among OC stocks within single mountain ranges (and study sites as well) tends to hide broader trends related to environmental factors, such as land-use and climate. For example, based on data from Table 33, in the European Alps, forest soils stock between 61 and 278 t/ha of OC, while grasslands (Photo 8) have average OC stocks in mineral horizons below 100 t/ha. Mountains in Mediterranean areas (such as the Apennines in Italy, Photo 9), the Pyrenees between France and Spain, and many mountain ranges in Spain store between 38 and 165 t/ha, with minor difference between forest and grassland soils.

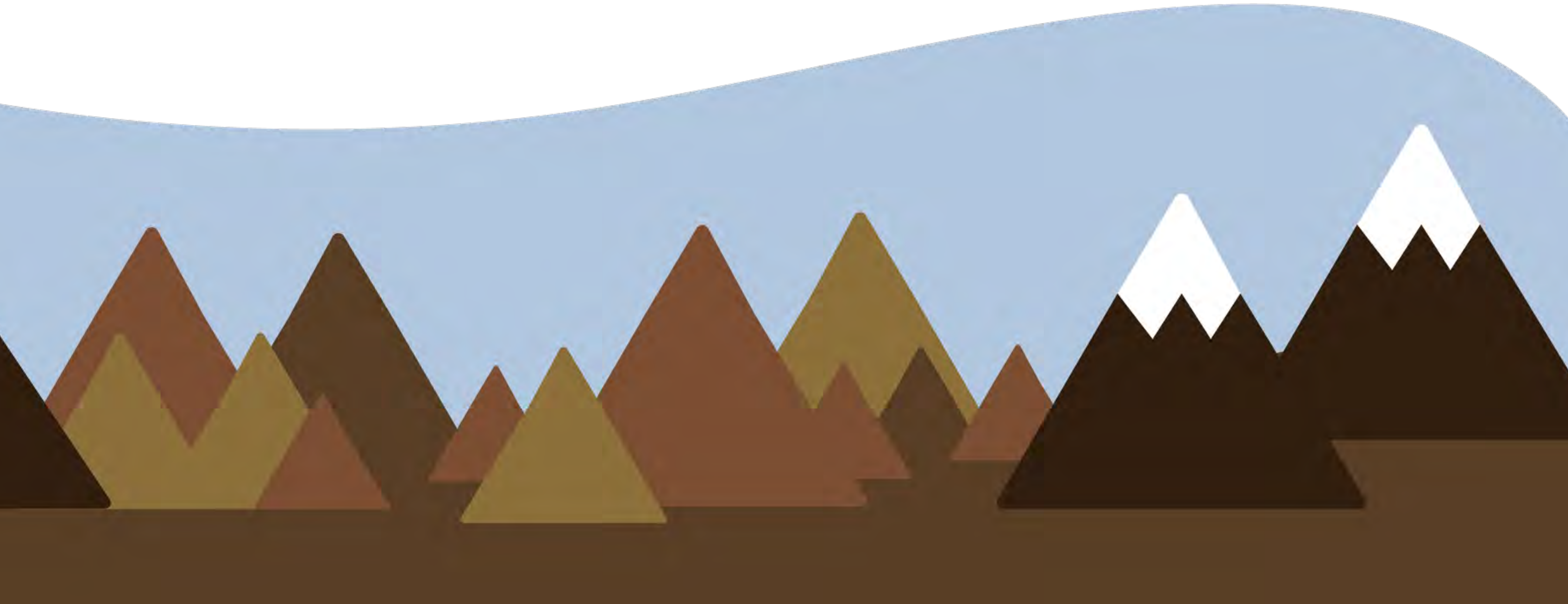

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Photo 8. Entic Umbric Podzol at 2600 m a.s.l on the southern slope of Mont Blanc (4810 m a.s.l. NW-Italian Alps)


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Photo 9. Shallow and stony but OC-rich Rendzic Leptosol in the alpine elevation belt in the Apennines, Central Italy

The SOC stock ranges shown in each work, however, are sometimes even larger. All these data exclude Histosols (peatland soils), as they are treated in a specific chapter (See hot-spot n°4 "Peatlands", this volume). In the Himalayas (9 articles), soil profiles store on average between up to ~ 400 t/ha of SOC (Photo 10); the huge elevation and climatic gradients, however, make these data poorly representative. Mountains in tropical areas tend to stock more SOC: for example, the first 70 cm of soil on Mount Cameroon stores 150–300 t/ha (with maximum values in rainforests, Tsozuè *et al.* 2019), while the steep slopes of SW Uganda (Twongyirwe *et al.* 2013) store up to 170 t/ha in the top 30 cm (Photo 11). Soils in the Usambara Mountains (Eastern Arc Mountains, Tanzania) store up to 270 t/ha in the top 100 cm.

Loss of OC is usually observed when land-use is changed from native forest to cultivation, particularly in the tropics. On the slopes of Mt. Kilimanjaro, for example, SOC stocks are reduced by ca. 23–38 percent when natural vegetation is removed to make space for cultivations (maize or coffee, Pabst *et al.* 2016). Tea plantations, however, can sometimes help soils store larger quantities of SOC compared to both degraded and primary forests (Chiti *et al.* 2018). Dinakaran *et al.* (2018) show how agricultural soils in the Himalayas are characterized by extremely depleted OC pools compared to forest or grassland soils.

The effect of land abandonment followed by shrub encroachment or reforestation, which are dominating processes in European mountains, is less clear, particularly in temperate areas (e.g. Campo *et al.* 2019).

Photo 10. A gentle slope along the Khumbu Valley (5065 m asl, Nepal), characterized by a C-rich Brunic Dystric Arenosol (Aeolic, Raptic)

Photo 11. Steep slopes covered by tropical montane rainforests in Bwindi National Park (SW Uganda), and nearby cultivated areas

4. Importance of mountain soil conservation for the provision of specific ecosystem services

Mountain soils provide many ecosystem services ranging from primary production to global climate regulation, by controlling C emissions into the atmosphere. They also provide a wide number of services related to water provision, filtration, and regulation that control the availability of pure water and groundwater recharge. Geitner *et al.* (2019) reviewed the main ecosystem services performed by mountain soils (in the Alpine Region) as the product of a unique combination of environmental conditions and soil properties, and listed them as:

- agricultural and forest biomass production;
- water retention;
- surface run-off regulation;
- local climate regulation;
- global climate regulation;
- water filtration and purification;

- nutrient cycle regulation;
- soil habitat & biodiversity;
- cultural & natural archives;
- recreational & spiritual services.

FAO (2019) estimated that, as of 2017, mountains were home to around 15 percent of the world population (about 1.1 billion people). Mountain soils benefit, in many ways, not only the people living in the world's mountains but also billions more living downstream. Mountains provide food, fodder, medicinal plants and other wood and non-wood forest products, and are recharge areas for water in aquifers used by a consistent part of the world's population. However, mountain people are still economically marginalized and heavily affected by poverty and high rates of vulnerability to food insecurity. According to the recent FAO data, as of 2017, one in two rural mountain dwellers living in developing countries were vulnerable to food insecurity (FAO, 2020). Vulnerability to food insecurity in rural mountain areas has been increasing since 2000, the first year when such data was monitored. The number of vulnerable people has increased in all regions of the developing world, but some have suffered more than others. Indeed, during the last 5 years, rural mountain dwellers in Africa saw the biggest increase in food insecurity. Between 2012 and 2017, more than 25 million rural mountain people have become vulnerable to food insecurity. Hence, the relevance of investing in mountain areas and protecting mountain soils to achieve the zero-hunger SDG goal becomes evident.

A wide range of soil ecosystem services is related with the water cycle, including the retention of water available to plants and the soil biota; the regulation of run-off, and thus the reduction of flooding and erosion risks through the balance with infiltration; water filtration, (the ability of soils to filter water, neutralizing or degrading potentially harmful substances), and contributions to the groundwater recharge. In particular, run-off regulation limits erosion rates and consequent nutrients loss on mountain slopes, where the soil formation rates are lowered by the harsh climate.

Mountains soils also act in climate regulation both at the local scale (through evapotranspiration, which cools down the air temperature and is especially relevant in urbanized areas) and on the global scale, through the storage of organic C that prevents its emission into the atmosphere as GHG. Additionally, forests are also known by being sinks of methane, a GHG with high warming capacity (e.g. Delmas *et al.,* 1992; Zhao *et al.* 2019b).

Among the other regulating services performed by mountain soils, is the ability to store, cycle and exchange nutrients with the other ecosystem components, thus preserving soil fertility and keeping healthy soils for food production. Soil management can largely contribute to enhance OC storage both in terms of amount and residence time (OC sink function).

Mountain soils also greatly contribute to biodiversity, hosting a huge variety of organisms living and growing in soils. The soil biodiversity expresses itself not only in terms of number and variety of species and individuals, but also in terms of the gene pool, and it's estimated to exceed the aboveground biodiversity.

Finally, soils also perform less visible services related to the aesthetic perception and the quality of the landscape, that are important for human well-being. Because of limited development in mountain regions, they can also host remnants of the past and give scientists many insights on past climate, vegetation, etc.

Given the variety of ecosystem services performed by mountain soils, the goal of sustainable soil management is fundamental if we want to keep mountain soils healthy and functioning to their full potential.

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Photo 12. Top: Vulnerable and eroded slopes after deforestation in the Kisoro District, SW Uganda (Bwindi mountains, with the Virunga Volcanoes in the background). Bottom: Diffused erosion affecting recently deforested slopes along the Rift Valley escarpment, Elgeyo-Marakwet County, Kenya

5. General challenges and trends

Besides soil ecosystems services, Geitner *et al.* (2019) also listed the main soil threats that can put mountain soils in danger. As soil ecosystem services are affected by chemical and physical properties such as texture, organic matter content, permeability, and structure, they can be negatively impacted by changes in these properties after natural or anthropogenic disturbance. Among the main threats putting at risk the functions of mountain soil, erosion and nutrients loss are particularly relevant in mountain areas where the effect of slope, combined with slow soil formation rates, can limit soil development. As well compaction (i.e. a significant reduction of soil porosity resulting from improper soil management practices (e.g. timber harvesting techniques, overgrazing…) can heavily affect mountain soils, compromising the infiltration capacity and the regulation of surface run-off, thus favoring accelerated erosion. Other threats are related to the loss of organic matter, which can affect both organic and mineral soils and can contribute to the release of greenhouse gases into the atmosphere. The loss of biodiversity can also alter mountain soils, and affect other services which are fundamental for healthy soils. Very often, soil threats (e.g. erosion and compaction) are triggered by land-use changes such as deforestation, and overgrazing (Photo 12 and Photo 14), urbanization, the building of infrastructures, or other disturbances (for example, wildfires). Soil sealing can also have negative effects on soil ecosystem services such as run-off regulation and biodiversity. This is particularly true in densely settled areas such as touristic resorts in the Alps, where the surface available for services and infrastructures is naturally limited by land conformation. The growth of tourism (for example, construction of ski runs, lifts, and hotels), the expansion of traffic, energy projects (including power lines, dams, hydroelectric plants, and reservoirs), intensified agricultural use, settlement development, and human-induced climate change are placing a growing impact on the environment. The soil in the Alps is not exempt from this development. Land use change and anthropogenic climate change result in severe sealing, erosion, and degradation.

The Member States of the Alpine Convention (AC) thus adopted the Soil Conservation Protocol at the 5th Alpine Conference in 1998, which is an instrument under international law that deals specifically and directly with soil conservation in a particular region (Markus, 2017). Specific attention has been dedicated to the protection of soils with particularly characteristic features, such as in wetland and moors, with the designation and management of endangered areas and areas threatened by erosion.

Attention and efforts by the scientific community, civil society, and international organizations have increased the awareness of the importance of mountain soils (for example, FAO, national and international soil science societies). In 2015 (UN International Year of Soils) FAO, a collaboration with the Mountain Partnership Secretariat[5], the Global Soil Partnership[6] and the University of Turin (Italy) promoted an awareness-raising campaign focused on mountain soils, with the publication of a book called “Understanding Mountain Soils”. More than 100 authors contributed to this book, through the presentation of worldwide case studies on the specificities of mountain soils, including their potential for climate change mitigation.

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[5] https://alpinesoils.eu/gspesp/mountain_p_secretariat/

[6] http://www.fao.org/global-soil-partnership/en/

The case studies ranged from oceanic alpine landscapes in Scotland (Britton *et al.*, 2015) including ecosystems typical of many mountain areas on the northwestern fringe of Europe, to the mountain wetlands of Lesotho (Mapeshoane, 2015). From these studies it appears clear that a better understanding of the mechanisms underlying the spatial variability in soil C stocks and fluxes is urgently needed, to predict the fate of mountain soil C under a changing climate and land-use.

6. General recommendations for the hotspot

To increase the effectiveness of mountain soils in OC sequestration, we can act in several ways to promote SOC accumulation and increase its residence time in soils that is, to delay its return into the atmosphere. Several guidelines can be proposed, but all of them are related to one or more of the following processes (Post and Kwon, 2000):

- increasing the input of organic matter (grazing, cover crops, afforestation...)
- changing the decomposability of organic matter, which is usually low in mountain areas due to harsh climate, by favoring its incorporation into the soil (for example, by enhancing mixing by organisms or by direct below-ground input)
- favouring the interaction between organic matter and the soil mineral phase, that is, promoting aggregation types that protect organic matter from fast mineralization
- developing effective guidelines aiming at maintaining and increasing the OC sequestration potential in mountain soils (Links4Soils, 2020)
- avoiding excessive irrigation, leading to nutrients loss and erosion. Drip irrigation or sub-irrigation are optimal systems in terms of water-use efficiency. Additionally, they minimize nutrients leaching and water erosion
- increasing organic matter content in agricultural soils with suitable fertilization. Apply animal manure and/or compost to improve soil aggregation through the input of organic matter. When possible, cover manure to limit the decline of soil fertility (i.e. via ammonia volatilization) and the dilution effect caused by rainfall and irrigation
- whenever possible, encouraging integrated systems (e.g. crop-livestock systems or crop-livestock-forest-systems, Photo 13), as well as reduced- or no-tillage practices that slow down the mineralization rate of the soil organic matter
- preserving the areas with carbon-rich soils such as peatlands and forests not only as OC reservoirs but also as unique sources of biodiversity
- avoiding or limit agricultural burning, especially in areas affected by erosion
- avoiding overgrazing leading to soil erosion on slopes and floods in lowlands. Organize pasture rotation and haymaking practices where possible.

Photo 13. Agroforestry in the Pare Mountains, Eastern Arc mountains, NE Tanzania

Photo 14. Erosion due to overgrazing (Kisimiri Chini, Mount Meru, Arusha District, Tanzania)

Table 19. Related cases studies available in volumes 4 and 6

Title	Region	Duration of study (Years)	Volume	Case-study n°
Reforestation of highlands in Javor Mountain, Republic of Srpska, Bosnia and Herzegovina	Europe	15	6	5
Natural afforestation of abandoned mountain grasslands along the Italian peninsula	Europe	23 to 72	6	6

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