Chapter 9
Are Soil Carbon Stocks in Mountain Grasslands Compromised by Land-Use Changes?

Jordi Garcia-Pausas, Joan Romanyà, Francesc Montané, Ana I. Rios, Marc Taull, Pere Rovira and Pere Casals

Abstract Mountain grasslands are generally rich in soil organic C, but the typical high spatial variability of mountain environments, together with the different management systems, makes their soil C content particularly variable. Socio-economic changes of the past decades have caused a progressive abandonment of the traditional use for grazing of some areas, while grazing pressure at easily accessible grasslands have increased. Here, we analyse the effect of these land-use changes on the factors regulating the soil C accumulation and stocks. Overgrazing generally leads to a reduction above- and below-ground litter inputs and a decrease in soil C stocks, affecting some soil physicochemical and biological properties. Additionally, the labile C inputs coming from animal faeces may accelerate the mineralisation of organic matter. Grazing abandonment causes a reduction of aboveground productivity, but the lack of consumption causes a short-term accumulation of organic matter. Its effect on belowground biomass and productivity is less clear. At longer term, grazing abandonment causes a change in the plant community composition, having the shrub encroachment the strongest effect on C storage. The low biochemical quality of shrub litter delays its decomposition and allows higher organic matter accumulation in the topsoil. But the effect of shrub proliferation at the deeper soil is less clear. The low root turnover of shrubs compared to grasses may reduce the C inputs to the soil. But, at the same time, the reduction of the root exudates may also reduce the microbial activity and the organic matter mineralisation.

J. Garcia-Pausas (✉) · F. Montané · A.I. Rios · M. Taull · P. Rovira · P. Casals
Forest Sciences Centre of Catalonia, CEMFOR-CTFC, Ctra de St. Llorenç de Morunys, km 2, 25280 Solsona, Catalonia, Spain
e-mail: jordi.gpausas@gmail.com

J. Romanyà
Department of Biology, Health and Environment, Universitat de Barcelona, Joan XXIII s/n, 08028 Barcelona, Catalonia, Spain

F. Montané
School of Natural Resources and the Environment, University of Arizona, Tucson, AZ 85721, USA

© The Author(s) 2017
J. Catalan et al. (eds.), High Mountain Conservation in a Changing World, Advances in Global Change Research 62, DOI 10.1007/978-3-319-55982-7_9
Keywords Grassland abandonment · Land-use changes · Mountain grasslands · Grazing intensification · Shrub encroachment · Soil organic carbon dynamics · Soil organic carbon stocks

9.1 Introduction

Soil organic matter plays essential roles in terrestrial ecosystems. It maintains the soil structure, favours water infiltration and reduces the risk of soil erosion. It also increases the water holding capacity of soils and, through its decomposition by soil biota, provides nutrients to the plants.

Carbon (C) comprises about 45% of the mass of soil organic matter. Plant photosynthetic activity produces organic matter using atmospheric CO$_2$, which is then accumulated in soil mainly by incorporating plant residues into the soil organic matter. Although this is the primary pathway by which atmospheric CO$_2$–C is incorporated into the soil, some additional atmospheric CO$_2$–C can also be sequestered in soil in inorganic forms by rock weathering and precipitation of Ca- and Mg-carbonates. Then, the oxidation of organic matter by soil microorganisms is the main process causing a release of carbon as CO$_2$ to the atmosphere, leaving less decomposable organic compounds, which are accumulated in the soil. Together with this biotic process, a significant amount of soil C can also be exported from the soil by leaching. Overall soil C sequestration results from the balance between the C flux from the atmosphere into the soil and the C release back to the atmosphere through microbial decomposition. This balance determines if soil behaves as a net sink for removing CO$_2$ from the atmosphere or a net source that contributes to rising atmospheric CO$_2$.

Soils represent the main compartment of organic C in most terrestrial ecosystems, containing globally about 1550 Pg C (1 Pg = 10$^{15}$ g), which roughly is twice the amount of C in the atmosphere (760 Pg C) and three times the amount in the biomass (550 Pg C) (Lal 2008). Given the large magnitude of these soil C stocks, potential reductions as little as 10% of the soil C content would equal to the anthropogenic CO$_2$ emitted over 30 years (Kirschbaum 2000), meaning significant changes in the atmospheric CO$_2$ concentrations and the reinforcement of the current global warming trend. So, there is a strong interest in avoiding C losses from soils and, if possible, to promote the C sequestration to mitigate the current greenhouse gases (GHG) emissions.

In this chapter, we summarise the special features of mountain alpine soils that contribute to explaining the organic C content and explore the challenges for soil C conservation due to changes in land management and use.

9.2 Mountain Soils and Their C Stocks

Mountain soils are generally steep, shallow, with relatively high erosion rates and influenced by harsh climatic conditions. Despite mountain ecosystems have much in common with those in high latitude, mountain soils are markedly different. These
differences originate from both climate and soil formation processes. High-altitude mountain ranges generally receive much higher rainfall, both in quantity and intensity (high torrentiality) than lowlands. Moreover, sunshine incidence in mountain slopes is usually higher than in high latitudes and largely depends on the aspect. In south-facing slopes solar radiation is high, even in winter time, thus reducing the snow cover and the chance of frost layers. In mountain ranges of temperate areas, even on north-facing slopes, winter temperatures are warmer than in high latitude areas and because of the higher precipitation the snow cover is thicker. Consequently, mountain soils are better insulated, with high solar radiation and thus their frost layer is less thick and not permanent in most cases. The reduction or lack of permafrost of the mountain soils contributes to their general good drainage and thus wet soils (i.e. peatlands) in mountain landscapes are mainly confined to bottom areas and depressions, and they are not widespread. Conversely, in mountain slopes high rainfall and good drainage speeds up soil formation processes. However, natural disturbances also linked to the slopes such as soil erosion, rock fall, landslides, avalanches and snow ablation play an important role in rejuvenating mountain soils. As a result of these complex interactions and because of its diverse geomorphology mountain landscapes hold a large spatial variability that is depicted in both soils and vegetation.

Soils of mountain areas tend to be young and highly influenced by their bedrock and physiographic properties. The wide range of soil types occurring in mountain regions is driven by microtopography, slope and aspect which, as stated above, define the snowpack and melting patterns that influence soil temperature, nutrient leaching and soil moisture (Stöhr 2007). Young mountain soils occur in well-drained areas and are classified as Leptosols or Regosols. Leptosols are thin soils, extremely gravelly and/or stony and with strong limitations to rooting. Regosols are weakly developed mineral soils in unconsolidated materials that occur in less stony areas and are typically highly erodible. On calcareous areas Rendzic or Chromic Leptosols dominate. Rendzic leptosols have a surface layer with high accumulation of organic matter and calcium carbonate. Chromic leptosols have a red surface layer and low or no calcium carbonate content. On siliceous bedrock, Regosols and the extremely thin Lithic leptosols are commonly found. But in stable and well-drained surfaces soils are often more developed, being common Dystric Cambisols and different types of Podzols. These latter two soil types show a thick and well-developed acidic horizon, but Podzols contain a subsurface horizon with illuvial amorphous organic matter and/or Al and Fe oxides. Finally, Histosols occur in poorly drained areas. These last soils evolve from incompletely decomposed plant remains and thus their features are quite independent of the bedrock type (IUSS Working Group WRB 2015).

Mountain soils in temperate areas usually have a high organic matter content, as shown in some regional soil C maps (Baritz et al. 2010; Doblas-Miranda et al. 2013). Although plant biomass in alpine grasslands is much lower than in forests, their soil C stocks are also generally high (Table 9.1) and comparable to forested areas (Berninger et al. 2015). The large amount of soil C in alpine environments is related to the high residence time of organic matter in the soil compared to the
Table 9.1 Some examples of soil organic C stocks in grasslands of the European mountains

| Mountains                        | C stocks (Mg ha\(^{-1}\)) | Altitude (m a.s.l.) | Annual mean air temperature (°C) | Plant formation                      | References |
|----------------------------------|-----------------------------|---------------------|----------------------------------|--------------------------------------|------------|
| Iberian Central System           | 72–324                      | 5                   | 1653–2051                        | Mesic grasslands                     | (1)        |
| Pyrenees                         | 45–365                      | 16                  | 1704–2092                        | Mesic grasslands                     | (1)        |
| Pyrenees                         | 65–300                      | 35                  | 1845–2900                        | Alpine and subalpine grasslands      | (2)        |
| Austrian Alps                    | 260 and 130                 | 2                   | 1700 and 1900                    | Alpine grassland, pine bushes and shrubs | (3)        |
| Swiss Alps                       | 53–116                      | 8                   | 810–2200                         | Grasslands                           | (4)        |
| Tatra Mountains                  | 20–250                      | 25                  | 1725–2368                        | Alpine meadows                       | (5)        |
| Eastern Swiss Alps               | 100                         | 6                   | 2616–2674                        | Alpine tundra with permafrost        | (6)        |
| Eastern Swiss Alps               | 150                         | 6                   | 2577–2695                        | Alpine tundra without permafrost     | (6)        |

(1) Montané et al. (2007); (2) Garcia-Pausas et al. (2007); (3) Djukic et al. (2010); (4) Leifeld et al. (2009); (5) Kopáček et al. (2006); (6) Zollinger et al. (2013)

*Annual mean air temperature at 2277 m a.s.l.

Living biomass (Körner 2003). This fact is caused by the harsh climatic conditions of the alpine environments that slow down the degradation of organic matter. Also, while forest soils receive large amounts of organic matter coming from above-ground biomass, in grasslands the primary organic matter inputs to the soil mainly come from root turnover and deposition. Consequently, the vertical distribution of organic C along the soil profile is typically shallower in forest soils than in grasslands (Jobbágy and Jackson 2000).

Mountain soils show a great variability in their characteristics. Thus, far from being evenly distributed, soil organic C content in mountain areas is particularly variable. Not only temperature reduces and precipitation increases with the elevation, but also the significant differences in solar radiation between north- and south-facing slopes, create environments that can be highly variable over relatively short distances. This feature, together with the high variability of soil depth and the natural diversity of substrates in mountain areas, makes the alpine landscapes a mosaic of different local conditions to the development of plant growth. This variability results in a considerable heterogeneity in plant community composition and structure, which in turn shape the distribution patterns of other organisms such
as arthropods, fungi and soil bacterial communities. Different land management practices (e.g. various grazing pressures in pastur... these factors result in soils with a highly heterogeneous amount of stored C, making difficult the prediction of current stocks and its response to the expected climate and land-use changes.

### 9.3 Factors Controlling Soil Organic C Stocks in Mountain Grasslands

The development of soil is a complex and continuous process, driven by parent material, climate and soil biota. In the mountains, the topography also plays an important role modifying the climate and creating different landforms for soil development. All these factors determine the physical, chemical and biological properties of soils and control their capacity to accumulate organic C.

#### 9.3.1 Bedrock Type

Mountain areas are often geologically complex, as a result of past volcanism, compression and tension faults, plate subduction and uplift. The parental material from which a soil develops determines many hydrological, ecological and pedogenic processes, having implications for the capacity of soils to store C, the C accumulation rates and its persistence in the soil. Differences in the lithology determine the differences in the mineral composition of soils and influence their texture, chemistry and weathering processes. Changes in plant composition and structure are also frequently associated with changes in the bedrock type through its effect on nutrient status and physical characteristics of the soil.

Soil texture is the most relevant characteristic that is determined by the bedrock type. For instance, soils developed on sandstones or granites usually have coarser textures than those developed on limestones or slates. Soil texture is particularly relevant for organic matter accumulation in soils, as organic matter is stabilised in soil through its interaction with the finest mineral particles. Indeed, organic matter associated with the finest particles (i.e. fine silt and clay) is usually older (Eusterhues et al. 2003) and has longer residence times (Balesdent 1996) than the organic matter in the coarser fractions. In the Pyrenees, although C and N availability were more important explaining topsoil basal respiration, soils developed on granites showed high rates of basal respiration (Garcia-Pausas et al. 2008), suggesting that they may contain a higher proportion of non-stabilised organic matter.
9.3.2 Climate

Carbon stocks are the result of the net balance between C inputs through primary production and C outputs through microbial mineralisation as well as leaching and erosion (Fig. 9.1).

In alpine areas, both primary production and microbial mineralisation are constrained by low temperatures, particularly during wintertime. Given that soils in the mountain areas have a relatively high amount of organic C, it can be suspected that microbial mineralisation might be more strongly limited by climate than primary production. However, there is some evidence that the maximum soil C stocks are found in the subalpine belt and that from that point upwards the soil organic C stocks tend to reduce with the elevation (Djukic et al. 2010), reaching close-to-zero levels at unvegetated substrates of extreme altitudes (Körner 2003). This reduction of C stocks is due to the reduced plant cover and productivity, reduced rooting depth, and also because soils are generally younger at high altitudes (Fig. 9.2). This general trend is expected to differ between the north- and south-facing slopes. Indeed, in the Pyrenees Garcia-Pausas et al. (2007) observed that the reduction in C stocks with altitude was sharper at the north-facing slopes, probably because at high altitudes the environmental conditions on the south-facing slopes are more favourable for plant growth (Fig. 9.3).

The microclimate environment also determines the characteristics of the soil organic matter and thus its turnover. There is an indirect effect mediated by climate-driven changes in the plant community composition and structure (see below), but also a direct effect of climatic conditions on organic matter quality. Soils developed on high altitudes are usually rich in labile and particulate organic C (Leifeld et al. 2009; Budge et al. 2011). As occurs with altitude, the severe conditions at the north-facing soils also cause a higher accumulation of poorly degraded organic matter than at south-facing slopes (Egli et al. 2015). These C pools appear to have long residence times, as shown by radiocarbon dating (Leifeld et al. 2009; Budge et al. 2011), which
Altitude is the primary factor of climatic heterogeneity in mountain landscapes, with high-altitude areas having generally low (−) temperatures and high (+) precipitation compared to low-altitude areas. It causes short growing seasons, low plant productivity and low soil C mineralisation rates (downwards arrows) in high-altitude sites compared to the bottom of the valleys. Photo: J. Garcia-Pausas

Predicted soil organic C stocks (SOCS) as a function of altitude and aspect in the Pyrenean subalpine and alpine grasslands. From Garcia-Pausas et al. (2007) with permission of Springer
is attributed to the harsh conditions for residue decomposition, the low soil pH and nutrient limitations. However, in areas where environmental conditions are unfavourable for decomposition, the degree of physicochemical stabilisation of organic matter, as measured by incubation under standard conditions, is lower (Garcia-Pausas et al. 2008). This feature could make these C pools particularly vulnerable to future climate and land-use changes.

The temperature variations in altitude and aspect, as well as the microtopography and the predominant wind direction largely determine the distribution and duration of the snowpack cover. The duration of the snowpack cover has important implications for the soil organic C dynamics, as it determines not only the temperature and moisture of the underlying soil but also the length of the plant growing season, the plant community composition, the microbial activity and nutrient dynamics. Indeed, snow cover maintains soil temperature relatively high compared to the air temperatures during winter, allowing the maintenance of unfrozen conditions (Edwards et al. 2007). This isolation is because of the low thermal conductivity of the snow, particularly when it is fresh and non-compacted (Körner 2003). Consequently, topsoil temperature under the snow is usually stable around 0 °C, even when air temperatures are far below zero. This allows the microbial processes to continue in winter (Schmidt and Lipson 2004), causing an increase in the winter CO₂ efflux (Walker et al. 1999) and also a faster decomposition of the leaf litter (Baptist et al. 2010; Saccone et al. 2013) under the snow than in non-covered soils. However, when the snowpack melts in late winter and before the snowfall in late autumn, soils are usually exposed to temperatures well below 0 °C, undergoing frequent episodes of freezing and thawing.

Soil frost does not allow the belowground plant production, but an earlier peak in fine root production during the subsequent growing season has been observed by Tierney et al. (2001) after an experimental snow removal in forest ecosystems. They also reported significant increases in fine root mortality, resulting in an increased root turnover. In grasslands, Kreyling et al. (2008) indicated that recurrent freeze–thaw events reduced root length during the subsequent growing season, but also increased aboveground productivity.

Freeze–thaw events alter C and N dynamics, affecting root production and turnover, soil microbial activity, soil C and N availability and its mineralisation. It has been observed that repeated freeze–thaw cycles as well as prolonged frost increase C and nutrient concentration in the soil solution, which can eventually be lost by leaching (Fitzhugh et al. 2001; Freppaz et al. 2007; Wipf et al. 2015). Also, a burst of CO₂ and N₂O emissions from thawing soils has often been observed (Nielsen et al. 2001; Teepe et al. 2001; Matzner and Borken 2008), as well as higher emissions during the subsequent growing season (Blankinship and Hart 2012). This response is partially explained by the decomposition of the microbial necromass (Herrmann and Witter 2002), but a reduction of microbial biomass in thawing episodes has not been detected in alpine soils (Lipson et al. 2002; Freppaz et al. 2007). Another source of the CO₂ flush when soil thaws is the death of fine roots due to the soil frost. The decomposition of the fine root litter increases the
CO₂ efflux from these soils, but the release of soluble cell constituents from dead fine roots is the main factor that contributes to the observed short-term CO₂ and N₂O pulse after thawing (Matzner and Borken 2008), and the higher concentrations of N and P in the soil solution (Fitzhugh et al. 2001; Freppaz et al. 2007; Wipf et al. 2015) after freeze–thaw events. The third source of the CO₂ flushed upon a freeze–thaw event is the change in the soil structure. Soil freezing causes a disruption of soil aggregates because the ice crystals expand breaking the bonds between mineral particles. This breakdown of the aggregates makes the organic matter protected within the aggregates available for microorganisms. Macroaggregates are more susceptible to these disruptive forces than microaggregates, and their vulnerability is enhanced with increasing soil water content, while high clay, organic matter and Fe-oxide concentrations reduce the disruptive effects of freezing (Six et al. 2004).

### 9.3.3 Plant Community Composition

The effect of abiotic environment on soil C content and its stability is in part mediated by its effect on plant communities. It is well known that abiotic factors determine the composition and characteristics of the plant community, which in mountain ecosystems is also strongly related to topography (Sebastià 2004) and bedrock type. The composition of plant communities determines some functional characteristics that can be relevant for the organic matter production and allocation. For instance, although most of the root characteristics are species-specific, Pohl et al. (2011) showed that in alpine ecosystems graminoids usually have a large proportion of fine roots compared to forbs or shrubs. This feature may enhance topsoil aggregate stability under grasses (Pohl et al. 2009), which could be relevant for stabilising C in soils. Other characteristics of the vegetation such as above- and belowground productivity and allocation, rooting depth, horizontal root expansion may influence the C inputs and its persistence in the soil.

Plant community composition is in turn related to the quality of soil organic matter and, consequently to its decomposition rates. The low quality for decomposition of the organic matter produced by woody shrubs, with high lignin and polyphenol content, greatly differs from that produced by herbaceous plants, which is much more readily decomposable. But also among herbaceous plants, there can be significant differences, as occurs with the N-enriched organic matter produced by legumes. Thus plant communities differing in the biochemical characteristics of the biomass can lead to differences in the biochemical quality of soil organic matter. Indeed, Eskelinen et al. (2009) indicated that high proportion of forbs in an alpine tundra of northern Europe were related to low soil C/N ratios and high soluble N/phenolics ratios, causing in turn differences in the associated microbial communities.
9.4 Effects of Land-Use and Management Changes on Soil C Dynamics and Stocks

Although at the global scale remote areas still exist in mountain regions, in temperate European mountains the diversity of habitats resulting from the complex topography and multiple microclimates has been shaped, similarly to the lowland, by the human activities for centuries (Montserrat and Fillat 1994; Gassiot Ballbé et al. 2017 in the present book). Over the past centuries, low-intensity agriculture, farming and forestry have created and structured semi-natural habitats that constitute the contemporary landscapes in temperate mountains (Fig. 9.4). For some of these habitats, the sustainability of ecosystem services, at least at short- and mid-term, is linked to the continuity of human involvement and may be threatened by changes in the historical use of the mountain ecosystems (MacDonald et al. 2000; Regato and Salman 2008).

Due to the inherent physical constraints of the vast majority of mountain valleys that prevented the modernization of agriculture, traditional and sustainable low-input farming systems had mainly remained invariable until the last decades (Plieninger et al. 2006). In recent times, however, the long agropastoral tradition was altered by the integration of local economies into the global market and the

![Fig. 9.4](image) Low-intensity agriculture and farming for centuries have shaped subalpine landscapes. Alinyà mountain, eastern Pre-pyrenees. Photo: Pere Casals
emergence of new values and interests. As a consequence, traditional and sus-
tainable multifunctional activities were abandoned and replaced by more purely
production-oriented ones. Pastures located on steep slopes and at higher altitudes,
requiring intensive labour, were abandoned while, at the same time, agriculture and
livestock raising in accessible fertile lowland fields and productive mountain
grazing has intensified (Tasser and Tappeiner 2002; Bartolomé et al. 2005;
Hopkins and Holz 2006). Changes in traditional farming practices have been
observed across the European mountains (MacDonald et al. 2000). In the Pyrenees,
traditional pastoral systems were characterised by an extensive management of the
herd and the local transhumance to the communal alpine pastures in summer. Also,
herds of sheep moved each year from the Ebro basin to summer mountain grass-
lands (Montserrat and Fillat 1994). In the last decades, in the Pyrenees, but also in
most of the temperate European mountains, the redirection of the labour force to
other employments, mainly related to the tertiary sector, caused changes in the
farming management practices. As a consequence, some farms were abandoned
while other intensified the management to accommodate socio-economic changes
and labour resources. Together with a decrease in the number of farms, an increase
of stocking number per farm and a shift of the stockbreeding to forms with low
labour requirements (i.e. ovine to bovine) are common trends that allowed
becoming more cost-efficient (Table 9.2).

| Table 9.2 | Change (%) in the number of farms and livestock heads during 1989–2009 in five counties of the Catalan Pyrenees |
|------------|--------------------------------------------------|
|            | Val d’Aran | Alta Ribagorça | Pallars Sobirà | Cerdanya | Ripollès |
| **Farms**  |           |               |            |          |          |
| Bovine     | −77       | −56           | −33        | −22      | −30      |
| Ovine      | −39       | −44           | −58        | −29      | −35      |
| **Livestock heads** | | | | | |
| Bovine     | −9        | 6             | 135        | 81       | 32       |
| Ovine      | 21        | −35           | −8         | −10      | −43      |

Elaborated using data from the Ministry of Agriculture, Livestock, Fisheries and Food (Government of Catalonia)

9.4.1 Grazing Intensification

The adjustment of traditional farm households to a more intensive production and
pluriactivity had entailed spatial changes in the grazing practices and land man-
agement. In the Pyrenees and Alps, the decline in shepherding has led to localised
concentrations of stock around more easy-to-reach alpine grasslands, frequently
resulting in overgrazing of high-quality pastures, while grazing intensity on steep
slopes will likely decline (MacDonald et al. 2000).
SOC is a function of the balance between inputs from primary production and outputs through decomposition (Fig. 9.1). As a result of overgrazing, the quantity of the inputs to the soil may be reduced due to the aboveground biomass removal by animals. Also, the reduced plant biomass (i.e. less photosynthetic tissue) in heavily grazed grasslands causes a reduction of the aboveground productivity in comparison to the non-grazed grasslands (Ferraro and Oesterheld 2002). Although grazing can stimulate aboveground plant productivity under light or moderate grazing intensities through the so-called compensatory growth, it has been shown that heavy defoliation may lead to substantial reduction of the aboveground production (Chen et al. 2006; Zhao et al. 2008). In this case, plants respond to defoliation by allocating more C aboveground and thus reducing root biomass and productivity. The magnitude of this effect increases with the intensity of defoliation, the nutrient availability and water availability (Zhao et al. 2008; Klumpp et al. 2009). So there are site-specific sustainable grazing regimes that allow the conservation of C stocks, but when that grazing pressures are exceeded, inputs into the soil may be reduced (Georgaidis et al. 1989; Ferraro and Oesterheld 2002; Gao et al. 2008).

Overgrazing causes an alteration in soil physical, chemical and biological properties, resulting in changes in vegetation cover, a degradation of soil and a loss of soil C stocks. A typical feature of grazing activity is spatial heterogeneity. Animals tend to graze on areas with the most nutritious plants whereas select particular landscapes features for resting and ruminating. As a consequence, different types of vegetation develop which, in turn, influences the subsequent behaviour of the animals. Plant nutrient contents and soil nutrient availability increase from grazed to resting areas (Badia et al. 2008). In highly grazed areas, in comparison with only lightly grazed ones, the availability of P increases as a consequence of cattle grazing and defecation, which may accelerate the P cycling (Güsewell et al. 2005). An increase in fresh organic C (i.e. faeces) and nutrient availabilities as a consequence of animal frequentation may increase the microbial decomposition of native soil organic C. In addition, an excess of trampling and continuous overgrazing increases the area of bare soil and the risk of soil erosion. In the Tibetan plateau, the degradation of grasslands due to land-use change and overgrazing caused relevant losses of soil organic C in the last 30 years (Xie et al. 2007). In the Alps, erosion rates can be considerably higher (4.4–20 Mg ha$^{-1}$ year$^{-1}$) on grasslands with clear signs of degradation of the vegetation cover (Meusburger and Alewell 2014).

### 9.4.2 Grazing Abandonment

Abandonment of pasturelands and traditional farming practices is a widespread phenomenon in the mountain areas of Europe (MacDonald et al. 2000). While the impacts on several environmental and landscape values are evident (Tasser et al. 2007), the effects on C dynamics and soil C stocks are less apparent. The net effects
of land-use changes on C stocks are the result of the changes in the inputs and output drivers in the short- and long term after abandonment. Land-use changes may also affect the biochemical quality of litter inputs, which is a major factor influencing the organic C accumulation in soils (Liao and Boutton 2008). In ecosystems with high belowground allocation, such as grasslands, root dynamics represent the primary source for building up soil organic matter (Rasse et al. 2005; Piñeiro et al. 2006). This situation mostly applies to grazed grasslands, where a substantial amount of aboveground production is removed by grazing animals. When grass species are not palatable, both above- and belowground productions may be of the same order of magnitude. For example, in subalpine Festuca eskia grasslands in the Pyrenees, Montané et al. (2010) estimated an aboveground production of about 200 g m$^{-2}$ year$^{-1}$ while the root production estimated by 15 cm-depth ingrowth cores was about 150 g m$^{-2}$ year$^{-1}$.

Belowground biomass production and turnover have been related to microclimate as well as to land-use management (Guo et al. 2007; Leifeld et al. 2015). In the short term, grazing abandonment of subalpine grasslands allows higher aboveground biomass and accumulation of substantial amounts of necromass, but the effects on belowground biomass remain controversial. In general, belowground productivity increases in response to grazing removal (Ruess et al. 1998; Johnson and Matchett 2001; Smit and Kooijman 2001) but some studies did not find significant effects (McNaughton et al. 1998; Bazot et al. 2005) or even negative effects (Frank et al. 2002; Pucheta et al. 2004). Controversial findings may be partly explained by the physiological responses of plants to defoliation, but also by changes in plant species composition that may translate to differences in productivity, C allocation patterns and rooting depths at the ecosystem level. Indeed, Lanta et al. (2009) reported changes in plant species composition and richness in a 3-year field experiment with grazing and abandonment, and also showed a reduction of belowground biomass in non-grazed grasslands of the White Carpathians in the Czech Republic. In a 2-year grazing exclusion experiment in the Pyrenees, root production decreased in grazed grasslands in comparison with non-grazed ones. This response occurred right after the grazing event, and no apparent effects on yearly belowground C input were found (Garcia-Pausas et al. 2011).

### 9.4.3 Soil C Stocks in Grazed and Ungrazed Mountain Grasslands

The effect of grazing abandonment on soil C stocks has mostly been studied through the comparison of grazed and ungrazed areas, but the short-term effects of grazing on SOC is inconsistent to date, with both increases and decreases reported in response to increased grazing pressure. Although the effect of herbivory on plant productivity and C allocation is still under debate, abandonment of light, extensive grazing management might reduce soil stocks (Schuman et al. 1999; Pucheta et al. 2004).
Thus in a survey of grasslands in the Pyrenees, we found that abandoned grasslands had lower SOC stocks in the uppermost 20 cm of soil than grazed ones (Casals et al. 2004). However, this result may just reflect that the less productive grasslands were abandoned. In summary, changes in soil C stocks of mountain grasslands as a consequence of grazing abandonment are, at least in the short term, small and no clear trends may be stated.

9.4.4 Effects of Shrub Encroachment on Soil C Dynamics and Stocks

In the long term, grazing abandonment may involve a change in the dominant functional groups and often leads to shrub encroachment (Fig. 9.5). This shift is often observed in many mountain areas (MacDonald et al. 2000) and can lead to long-term expansion of forests (Gehrig-Fasel et al. 2007; Amétegui et al. 2010). Shrub encroachment into grasslands has been documented in the Pyrenees (Molinillo et al. 1997; Roura-Pascual et al. 2005) and the Central System ranges of the Iberian Peninsula (Sanz-Elorza et al. 2003). However, depending on the site characteristics, this can be a slow process. Indeed, Pardo et al. (2015) did not

Fig. 9.5 Shrub encroachment (*Cytisus balansae* ssp. *europaeus*) into mountain grasslands. Durro mountains (Alta Ribagorça, Central Pyrenees). Photo: Pere Casals
observe great changes in vegetation richness and composition after two decades of grazing exclusion in subalpine grasslands in the central Pyrenees. In Collada de Montalto (Central Pyrenees), shrub encroachment occurred mostly in grass patches inside the shrublands while woody proliferation into open grassland was less evident. Comparing the border between grassland and shrubland, we estimated a mean shrub expansion of the border into the mesic grassland of 2.0 ± 1.4 m (n = 263) in the period between 1997 and 2014 (unpublished data).

When woody plant invasion occurs, the shift from grass- to a shrub-dominated ecosystem entails significant changes in the production and placement of the inputs of litter (i.e. aboveground or belowground) and on factors that regulate soil organic matter mineralisation such as microclimate, biochemical quality of organic matter and the structure of the microbial community.

### 9.4.4.1 Litter Inputs

After shrub encroachment, the pattern of litter inputs changes from a belowground predominance in grasslands to an increase of aboveground deposition in shrublands. This shift is due to the differential allocation patterns between grasses and shrubs (Lett et al. 2004). For instance, in *Cytisus balansae* shrublands that had invaded subalpine grasslands of the Pyrenees, aboveground litter input was estimated as high as fourfold the root litter inputs in the top 15 cm of soil (Montané et al. 2010).

Surface litter is partially decomposed to CO₂, but a fraction is incorporated into the mineral horizons as a dissolved or particulate organic matter where it is mineralised or stabilised. Indeed, litter layers under shrubs may be an important source of dissolved organic C into the mineral soil, with a flux that may represent up to 35% of the annual litterfall C (Kalbitz and Kaiser 2008). Also, free particulate organic matter plays a significant role in the increase of soil organic C in the uppermost layers after woody plant encroachment in grasslands (Liao et al. 2006). Consequently, shrub encroachment into grasslands modifies the amount and placement of organic matter into the soil, but the effect on C sequestration also depends on the C loss from decomposing litter and soil organic matter.

### 9.4.4.2 Microclimate

Changes in the plant cover after pasture abandonment and shrub encroachment modify incoming solar radiation and precipitation to the soil. After grazing removal, the accumulation of standing necromass and litter reduces soil temperature and may increase soil water content (Rosset et al. 2001). In the Pyrenees, cumulative degree-days above 0 °C from May to November at 5 cm-depth soil were about 20% lower beneath woody canopies than under grasses (Montané et al. 2010). Lower
temperatures under shrub canopies likely reduces above- and/or belowground litter decomposition which may be the predominant mechanism behind higher SOC after shrub encroachment (Smith and Johnson 2004). For instance, a reduction of soil CO₂ efflux after grazing exclusion in the Tibetan Plateau has been attributed in part to its lower soil temperature (Chen et al. 2016). In the Pyrenees, Festuca eskia roots incubated for 1 year in buried litterbags in a subalpine soil decomposed slightly slower under shrubs than in paired grasslands (20.1 ± 0.42% and 22.4 ± 1.44% mass loss, respectively) (Casals et al. 2010). In addition, using buried labelled wheat roots mixed with soil, Casals et al. (2010) showed that ¹³C loss was about four percent units lower in root bags incubated for 1 year in non-grazed grassland plots and seven percent units lower under shrubs than in paired grazed grasslands. As these results derived from the incubation of standard labelled material, they mainly reflect a change to a less favourable soil environment for root decomposition due to either grazing exclusion or shrub encroachment. Therefore, a decrease in soil temperature may contribute to explain lower root decomposition rates after grassland abandonment and shrub encroachment.

**9.4.4.3 Biochemical Quality and Microbial Activity**

It is widely known that litter nutrient concentration and organic matter quality (e.g. lignin content) are the main factors determining litter decomposition rates (Cornwell et al. 2008). Grasslands typically have a high density of fine roots that are poorly lignified and with high turnover rates, thus providing a relatively labile C substrate for microbial activity. In contrast, the proliferation of shrubs may increase the presence of lignified roots with lower turnover rates. After shrub encroachment, low quality of litter inputs, with large amounts of secondary compounds such as lignin or polyphenolic substances, may hinder decomposition and promote C accumulation (Pérez-Harguindeguy et al. 2000; Shaw and Harte 2001; McCulley et al. 2004; Liao and Boutton 2008).

The biochemical quality of litter may differ between species. In the Pyrenees, an aboveground litter of grasses showed marked differences in the chemical composition from that of the two main invading shrubs of that area (Cytisus balansae and Juniperus communis). The litter of both shrubs had higher concentrations of recalcitrant compounds (e.g. lignin, lipids, suberin) and a low concentration of either N (conifer) or P (legume) relative to grass litter (Montané et al. 2010). Consequently, the higher organic C found in the upper mineral soil layer under shrubs compared to the grassland was mainly attributed to the slower decomposition of shrub litter and the transfer of litter-derived C into the soil. However, the presence of grass litter, with high N and P concentrations, may enhance microbial activity and prime the decomposition of recalcitrant shrub litter. As a result, at least in the short term after shrub proliferation when both shrub and grass litters coexist, the shrub litter accumulation pattern is altered (Montané et al. 2013).
Defoliation induces an increase of root exudation (Paterson et al. 2005). Therefore when grassland is abandoned a reduction of labile C inputs into the soil can be expected. Also, when shrubs proliferate, their lower fine root density may cause further reduction of C inputs by exudation. This decrease of labile C release from roots may cause a significant reduction of microbial activity (Hamilton and Frank 2001) and also a lower stimulation of soil organic matter mineralisation (i.e. priming) that usually occurs in the presence of labile C (Kuzyakov et al. 2000). Priming effect on soil organic matter mineralisation is particularly relevant in the rhizosphere and, although its magnitude is variable, it increases with the rate of rhizospheric C inputs (Paterson and Sim 2013) and may account for a substantial fraction of the SOM-derived CO₂ efflux (Cheng and Kuzyakov 2005). In addition, this reduction of priming effect may cause in turn a reduction of the nutrient availability for plants (Hamilton and Frank 2001).

The change of root exudates, as well as the fate of particulate organic matter also promotes a change in the microbial community composition (Grayston et al. 2004). Indeed, fungal growth and activity seems to be generally favoured in surface horizons after grazing or agricultural abandonment (Zornoza et al. 2009; Lopez-Sangil et al. 2011) and a higher fungal-to-bacterial activity ratio seems to promote a conservative cycling of nutrients in soil and C accumulation (Wardle et al. 2004; Gordon et al. 2008). Therefore a reduction in soil organic C decomposition in abandoned sites is expected.

### 9.4.4.4 Soil C Stocks in Shrub-Encroached Grasslands

In summary, shrub encroachment into mountain grasslands increases soil organic carbon in the upper soil mineral profile compared to the grassland soil (Montané et al. 2007). This net C increase may be explained by lower aboveground and belowground litter decomposition after shrub proliferation due to lower soil temperatures and lower biochemical quality of shrub organic matter. Lower litter quality may promote a shift in the composition of the microbial community to a slow-growth strategy, typical of a fungal-dominated microbial community (Bardgett et al. 2005), which may contribute to explain lower decomposition. The reduction of fine root density with the proliferation of shrubs may also reduce the rates of root exudation, which may decrease the priming effect on soil organic matter mineralisation thus contributing to the conservation of soil C stocks.

### 9.4.4.5 Shrubland Management and Soil C Stocks

Shrub encroachment into grasslands involves the replacement of one dominant growth form by another one, and it is likely to impact on ecosystem structure and functions (Lett and Knapp 2005). In the Pyrenees, a decrease in diversity
(Anthelme et al. 2007) and increases in soil C storage (Montané et al. 2007) have been reported after shrub proliferation into grasslands. Woody encroachment increases the risk of fire propagation by incrementing both fuel load and fuel continuity. In these encroachment-prone communities, managers may have to decide between reducing shrub proliferation to maintain biodiversity and grazing potential or allowing the shrub proliferation to increase C sequestration.

In the Pyrenees, shepherds have traditionally used fire as a management tool to improve grass productivity and transform encroached land into grassland. Today prescribed burning is usually carried out by fire brigades or foresters in winter when snowy or wet conditions limit the impact of the fire on soils and herbaceous plants (Rigolot et al. 2002). Mechanical thinning is also applied to revert encroached grasslands. How these management options affect organic matter dynamics and soil C stocks remains an issue.

9.5 Conclusions and Further Research Needs

Agricultural land-use changes in the European mountains show antagonist trends, intensification at the bottom of valleys and other productive grasslands, whereas the less productive grasslands located on steep slopes and at higher altitudes are being increasingly abandoned. A mechanistic understanding of how these changes affect relevant ecological processes, such as biodiversity or C stocks, is necessary to predict the effects of global change on ecosystem function and deliver appropriate management recommendations.

The decline of agropastoral activities is especially pervasive in high mountain grasslands. As a consequence, pasture abandonment, especially of marginal and less productive lands, and shrub encroachment into grasslands have become the most significant trends in land use, which may be observed all around European mountains, to a greater or lesser extent. Short-term changes in soil C stocks as a consequence of grazing abandonment are difficult to detect due to the large size of the organic matter pool as compared to the small changes in the C inputs, and also to the high spatial variability of soil C stocks (Conant and Paustian 2002; Smith 2004). Smith (2004), using a modelling approach, demonstrated that a change in SOC may not be detectable until about 7–10 year after the experiment, assuming an increase in soil C input of 20–25% (Smith 2004). Therefore, well monitored long-term exclusion experiments would be very useful to measure changes in the C stocks caused by management changes.

Higher soil organic matter after shrub encroachment into grasslands may be explained by the high content of recalcitrant compounds such as lignin and polyphenols in the plant-derived organic matter inputs, which slows the decomposition of soil organic matter and delays its incorporation into the protected pools in the mineral soil.

Due to high fine root density and rhizosphere exudation rates, grassland soils show higher priming effect on C mineralisation than in woodland soils (Waldrop
and Firestone 2004). The effect of woody plant invasion on rhizosphere priming is still unknown and could have a significant impact on C balance.

Acknowledgements This study summarises the work done in different research projects funded by the Ministerio de Economía y Competitividad, Spain (Carbopas, REN2002-04300-C02-02; VULCA, CGL2005-08133-C03; GRACCIE Consolider Program, CSD2007-00067) and by the European Commission (GHG-Europe project, FP7-ENV-2009-1, project No. 244122). J.G.P. and P.C. are financially supported by the Spanish Ministerio de Economía y Competitividad, through Juan de la Cierva and Ramón y Cajal contracts, respectively.

References

Améztegui A, Brotons L, Coll L (2010) Land-use changes as major drivers of mountain pine (Pinus uncinata Ram.) expansion in the Pyrenees. Glob Ecol Biogeogr 19:632–641

Anthelme F, Villaret JC, Brun JJ (2007) Shrub encroachment in the Alps gives rise to the convergence of sub-alpine communities on a regional scale. J Veg Sci 18:355–362

Badia D, Martí C, Sánchez JR, Fillat F, Aguirre J, Gómez D (2008) Influence of livestock soil eutrophication on floral composition in the Pyrenees mountains. J Mt Sci 5:63–72

Balesdent J (1996) The significance of organic separates to carbon dynamics and its modelling in some cultivated soils. Eur J Soil Sci 47:485–493

Baptist F, Yoccoz NG, Choler P (2010) Direct and indirect control by snow cover over decomposition in alpine tundra along a snowmelt gradient. Plant Soil 328:397–410

Bardgett RD, Bowman WD, Kaufmann R, Schmidt SK (2005) A temporal approach to linking aboveground and belowground ecology. Trends Ecol Evol 20:534–641

Baritz R, Seufert G, Montanarella L, Van Ranst E (2010) Carbon concentrations and stocks in forest soils of Europe. For Ecol Manag 260:262–277

Bartolomé J, Lopez ZG, Broncano MJ, Plaixats J (2005) Grassland colonization by Erica scoparia (L.) in the Montseny Biosphere Reserve (Spain) after land-use changes. Agr Ecosyst Environ 111:253–260

Bazot S, Mikola J, Nguyen C, Robin C (2005) Defoliation-induced changes in carbon allocation and root soluble carbon concentration in field-grown Lolium perenne plants: do they affect carbon availability, microbes and animal trophic groups in soil? Funct Ecol 19:886–896

Berninger F, Susiluoto S, Gianelle D, Bahn M, Wohlfahrt G, Sutton M, Garcia-Pausas J, Gimeno C, Sanz MJ, Dore S, Rogiers N, Furger M, Eugster W, Balzarolo M, Sebastià MT, Tenhunen J, Staszewski T, Cernusca A (2015) Management and site effects on carbon balances of European mountain meadows and rangelands. Boreal Environ Res 20:748–760

Blankinship JC, Hart SC (2012) Consequences of manipulated snow cover on soil gaseous emission and N retention in the growing season: a meta-analysis. Ecosphere 3, art 1

Budge K, Leifeld J, Hilbrunner E, Fuhrer J (2011) Alpine grassland soils contain large proportion of labile carbon but indicate long turnover times. Biogeosciences 8:1911–1923

Casals P, Garcia-Pausas J, Romanya J, Camarero L, Sanz MJ, Sebastià MT (2004) Effects of livestock management on carbon stocks and fluxes in grassland ecosystems in the Pyrenees. In: Lüscher et al (eds) in land use systems in grassland dominated regions, Grassland science in Europe, vol 9. Swiss Grassland Society (AGFF), Zürich, pp 136–138

Casals P, Garcia-Pausas J, Montané F, Romanya J, Rovira P (2010) Root decomposition in grazed and abandoned dry Mediterranean dehesa and mesic mountain grasslands estimated by standard labelled roots. Agr Ecosyst Environ 139:759–765

Chen J, Zhuo X, Wang J, Hruska T, Shi W, Cao J, Zhang B, Xu G, Chen Y, Luo Y (2016) Grazing exclusion reduced soil respiration but increased its temperature sensitivity in a Meadow Grassland on the Tibetan Plateau. Ecol Evol 6:675–687
Chen Y, Lee P, Lee G, Mariko S, Oikawa T (2006) Simulating root responses to grazing of a Mongolian grassland ecosystem. Plant Ecol 183:265–275

Cheng W, Kuzyakov Y (2005) Root effects on soil organic matter decomposition. In: Zobel RW, Wright SF (eds) Roots and soil management: interactions between roots and the soil. Agronomy monograph no 48. ASA, CSSA and SSSA, Madison, Wisconsin, pp 119–143

Conant RT, Paustian K (2002) Spatial variability of soil organic carbon in grasslands: implications for detecting change at different scales. Environ Pollut 116:127–135

Cornwell WK, Cornelissen JHC, Amatangelo K, Dorrepaal E, Eviner VT, Godoy O, Hobbie SE, Hooijens B, Kurokawa H, Pérez-Harguindeguy N, Quested HM, Santiago LS, Wardle DA, Wright IJ, Aerts R, Allison SD, van Bodegom P, Brovkin V, Chatain A, Callaghan TV, Díaz S, Garnier E, Gurvich DE, Kazakou E, Klein JAL, Read J, Reich P, Soudzilovskaia NA, Vaieretti MV, Westoby M (2008) Plant species traits are the predominant control on litter decomposition rates within biomes worldwide. Ecol Lett 11:1065–1071

Djukic I, Zehetner F, Tatzber M, Gerzabek MH (2010) Soil organic-matter stocks and characteristics along an Alpine elevation gradient. J Plant Nutr Soil Sci 173:30–38

Doblas-Miranda E, Rovira P, Brotons L, Martinez-Vilalta J, Retana J, Pla M, Vayreda J (2013) Soil carbon stocks and their variability across the forests, shrublands and grasslands of peninsular Spain. Biogeosciences 10:8353–8361

Edwards AC, Scalenghe R, Freppaz M (2007) Changes in the seasonal snow cover of alpine regions and its effect on soil processes: a review. Quat Int 172:162–163

Egli M, Lessovaia SN, Chistyakov K, Inozemzev S, Polekovsky Y, Ganyushkin D (2015) Microclimate affects soil chemical and mineralogical properties of cold alpine soils of the Altai Mountains (Russia). J Soil Sediment 15:1420–1436

Eskelinen A, Stark S, Männö M (2009) Links between plant community composition, soil organic matter quality and microbial communities in contrasting tundra habitats. Oecologia 161:113–123

Eusterhues K, Rumpel C, Kleber M, Kögel-Knabner I (2003) Stabilisation of soil organic matter by interactions with minerals as revealed by mineral dissolution and oxidative degradation. Org Geochem 34:1591–1600

Ferraro DO, Oesterheld M (2002) Effect of defoliation on grass growth: a quantitative review. Oikos 98:602–606

Fitzhugh RD, Driscoll CT, Groffman PM, Tierney GL, Fahey TJ, Hardy JP (2001) Effects of soil freezing, disturbance on soil solution nitrogen, phosphorus, and carbon chemistry in a northern hardwood ecosystem. Biogeochemistry 56:215–238

Frank DA, Kuns MM, Guido DR (2002) Consumer control of grassland plant production. Ecology 83:602–606

Freppaz M, Williams BL, Edwards AC, Scalenghe R, Zanini E (2007) Simulating soil freeze/thaw cycles typical of winter alpine conditions: Implications for N and P availability. Appl Soil Ecol 35:247–255

Gao YZ, Giese M, Lin S, Sattelmacher B, Zhao Y, Brueck H (2008) Belowground net primary productivity and biomass allocation of grassland in Inner Mongolia is affected by grazing intensity. Plant Soil 307:41–50

Garcia-Pausas J, Casals P, Cameron L, Huguet C, Sebastià MT, Thompson R, Romanyà J (2007) Soil organic carbon storage in mountain grasslands of the Pyrenees: effects of climate and topography. Biogeochemistry 82:279–289

Garcia-Pausas J, Casals P, Cameron L, Huguet C, Thompson R, Sebastià MT, Romanyà J (2008) Factors regulating carbon mineralization in the surface and subsurface soils of Pyrenean mountain grasslands. Soil Biol Biochem 40:2803–2810

Garcia-Pausas J, Casals P, Romanyà J, Vallecillo S, Sebastià MT (2011) Seasonal patterns of belowground biomass and productivity in mountain grasslands in the Pyrenees. Plant Soil 340:315–326

Gassiot Ballbé E, Mazzucco N, Clemente Conte I, Rodríguez Antón D, Obea Gómez L, Quesada Carrasco M, Díaz Bonilla S (2017) The beginning of high mountain occupations in the Pyrenees. Human settlements and mobility from 10,500 cal BP to 4500 cal BP. In: Catalan J,
Ninot JM, Aniz MM (eds) Challenges for high mountain conservation in a changing world. Springer, pp 75–105

Gehrig-Fasel J, Guisan A, Zimmermann NE (2007) Tree line shifts in the Swiss Alps: climate change or land abandonment? J Veg Sci 18:571–582

Georgaidis NJ, Ruesch RW, McNaughtib SJ (1989) Ecological conditions that determine when grazing stimulates grass production. Oecologia 96:157–161

Gordon H, Haygarth PM, Bardgett RD (2008) Drying and rewetting effects on soil microbial community composition and nutrient leaching. Soil Biol Biochem 40:302–311

Grayston SJ, Campbell CD, Bardgett RD, Mawdsley JL, Clegg CD, Ritz K, Griffiths BS, Rodwell JS, Edwards SJ, Davies WJ, Elston DJ, Millard P (2004) Assessing shifts in microbial community structure across a range of grasslands of differing management intensity using CLPP, PLFA and community DNA techniques. Appl Soil Ecol 25:63–84

Guo LBB, Wang MB, Gifford RM (2007) The change of soil carbon stocks and fine root dynamics after land use change from native pasture to a pine plantation. Plant Soil 299:251–262

Güsewell S, Jewell PL, Edwards PJ (2005) Effects of heterogeneous habitat use by cattle on nutrient availability and litter decomposition in soils of an Alpine pasture. Plant Soil 268:135–149

Hamilton EW III, Frank DA (2001) Can plants stimulate soil microbes and their own nutrient supply? Evidence from a grazing tolerant grass. Ecology 82:2397–2402

Herrmann A, Witter E (2002) Sources of C and N contributing to the flush in mineralization upon freeze-thaw cycles in soils. Soil Biol Biochem 34:1495–1505

Hopkins A, Holz B (2006) Grassland for agriculture and nature conservation: production, quality and multi-functionality. Agron Res 4:3–20

IUSS Working Group WRB (2015) World reference base for soil resources 2014, update 2015 international soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No 106. FAO, Rome

Jobbágy EG, Jackson RB (2000) The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecol Appl 10:423–436

Johnson LC, Matchett JR (2001) Fire and grazing regulate belowground processes in tallgrass prairie. Ecology 82:3377–3389

Kalbitz K, Kaiser K (2008) Contribution of dissolved organic matter to carbon storage in forest mineral soils. J Plant Nutr Soil Sci 171:52–60

Kirschbaum MUF (2000) Will changes in soil organic carbon act as a positive or negative feedback on global warming? Biogeochemistry 48:21–51

Klumpp K, Fontaine S, Attard E, Le Roux X, Gleixner G, Soussana JF (2009) Grazing triggers soil carbon loss by altering plant roots and their control on soil microbial community. J Ecol 97:876–885

Kopáček J, Kaňa J, Šantrůčková H (2006) Pools and composition of soils in the alpine zone of the Tatra Mountains. Biologia, Bratislava 61(Suppl 18):S35–S49

Körner C (2003) Alpine plant life. Functional plant ecology of high mountain ecosystems, 2nd edn. Springer

Kreyling J, Baierkuhlein C, Pritsch K, Schloter M, Jentsch A (2008) Recurrent soil freeze-thaw cycles enhance grassland productivity. New Phytol 177:938–945

Kuzyakov Y, Friedel JK, Stahr K (2000) Review of mechanisms and quantification of priming effects. Soil Biol Biochem 32:1485–1498

Lal R (2008) Carbon sequestration. Philos T R Soc B 363:815–830

Lanta V, Doležal J, Lantová P, Kelišek J, Mudrák O (2009) Effects of pasture management and fertilizer regimes on botanical changes in species-rich mountain calcareous grassland in Central Europe. Grass Forage Sci 64:443–453

Leifeld J, Zimmermann M, Fuhrer J, Conen F (2009) Storage and turnover of carbon in grassland soils along an elevation gradient in the Swiss Alps. Glob Change Biol 15:668–679

Leifeld J, Meyer S, Budge K, Sebastià MT, Zimmermann M, Fuhrer J (2015) Turnover of grassland roots in mountain ecosystems revealed by their radiocarbon signature: role of temperature and management. PLoS ONE 10(3):e0119184. doi:10.1371/journal.pone.0119184
Lett MS, Knapp AK (2005) Woody plant encroachment and removal in mesic grassland: production and composition responses of herbaceous vegetation. Am Midl Nat 153:217–231
Lett MS, Knapp AK, Briggs JM, Blair JM (2004) Influence of shrub encroachment on aboveground net primary productivity and carbon and nitrogen pools in a mesic grassland. Can J Bot 82:1363–1370
Liao JD, Botton TW (2008) Soil microbial biomass response to woody plant invasion of grassland. Soil Biol Biochem 40:1207–1216
Liao JD, Botton TW, Jastrow JD (2006) Storage and dynamics of carbon and nitrogen in soil physical fractions following woody plant invasion of grassland. Soil Biol Biochem 38:3184–3196
Lipson DA, Schadt CW, Schmidt SK (2002) Changes in soil microbial community structure and function in an alpine dry meadow following spring snow melt. Microb Ecol 43:307–314
Lopez-Sangil L, Rousk J, Wallander H, Casals P (2011) Microbial growth rate measurement reveal that land-use abandonment promotes a fungal dominance of SOM decomposition in grazed Mediterranean ecosystems. Biol Fert Soils 47:129–138
MacDonald D, Crabtree JR, Wiesinger G, Stamou N, Fleury P, Gutierrez Lazpita J, Gibon A (2000) Agricultural abandonment in mountain areas of Europe: environmental consequences and policy response. J Environ Manage 59:47–69
Matzner E, Borken W (2008) Do freeze-thaw event enhance C and N losses from soils of different ecosystems? A review. Eur J Soil Sci 59:274–284
McCulley RL, Archer SR, Botton TW, Hons FM, Zuberer DA (2004) Soil respiration and nutrient cycling in wooded communities developing in grasslands. Ecology 85:2804–2817
McNaughton SJ, Banyikwa FF, McNaughton MM (1998) Root biomass and productivity in a grazing ecosystem: the Serengeti. Ecology 79:587–592
Meusburger K, Alewell C (2014) Soil erosion in the Alps. Experience gained from case studies (2006–2013). Federal Office for the Environment, Bern. Environmental Studies No 1408, 116 pp
Molinillo M, Lasanta T, García Ruiz JM (1997) Managing mountainous degraded landscapes after farmland abandonment in the central Spanish Pyrenees. Environ Manag 21:587–598
Montané F, Rovira P, Casals P (2007) Shrub encroachment into mesic mountain grasslands in the Iberian Peninsula: effects of plant quality and temperature on soil C and N stocks. Glob Biogeochem Cy 21:GB4016. doi:10.1029/2006GB002853
Montané F, Romanyà J, Rovira P, Casals P (2010) Aboveground litter quality changes may drive soil organic carbon increase after shrub encroachment into mountain grasslands. Plant Soil 337:151–165
Montané F, Romanyà J, Rovira P, Casals P (2013) Mixtures with grass litter may hasten shrub litter decomposition after shrub encroachment into mountain grasslands. Plant Soil 368:459–469
Montserrat P, Fillat F (1994) The systems of grassland management in Spain. In: Breymeyer A (ed) Managed grasslands. Elsevier, B.V., Amsterdam
Nielsen CB, Groffman PM, Hamburg SP, Driscoll CT, Fayey TJ, Hardy JP (2001) Freezing effects on carbon and nitrogen cycling in northern hardwood forest soils. Soil Sci Soc Am J 65:1723–1730
Paldo I, Doak DF, García-González R, Gómez D, García MB (2015) Long-term response of plant communities to herbivore exclusion at high elevation grasslands. Biodivers Conserv 24:3033–3047
Paterson E, Sim A (2013) Soil-specific response functions of organic matter mineralization to the availability of labile carbon. Glob Change Biol 19:1562–1571
Paterson E, Thornton B, Midwood AJ, Sim A (2005) Defoliation alters the relative contributions of recent and non-recent assimilate to root exudation from Festuca rubra. Plant Cell Environ 28:1525–1533
Pérez-Harguindeguy N, Díaz S, Cornelissen JHC, Vendramini F, Cabido M, Castellanos A (2000) Chemistry and toughness predict leaf litter decomposition rates over a wide spectrum of functional types and taxa in central Argentina. Plant Soil 218:21–30
Piñeiro G, Paruelo JM, Oesterheld M (2006) Potential longterm impacts of livestock introduction on carbon and nitrogen cycling in grasslands of Southern South America. Glob Change Biol 12:1267–1284

Plieninger T, Höcht F, Spek T (2006) Traditional land-use and nature conservation in European rural landscapes. Environ Sci Policy 9:317–321

Pohl M, Alig D, Körner C, Rixen C (2009) Higher plant diversity enhances soil stability in disturbed alpine ecosystems. Plant Soil 324:91–102

Pohl M, Stroude R, Buttler A, Rixen C (2011) Functional traits and root morphology of alpine plants. Ann Bot-London 108:537–548

Pucheta E, Bonamici I, Cabido M, Díaz S (2004) Below-ground biomass and productivity of a grazed site and a neighbouring ungrazed exclosure in a grassland in central Argentina. Austral Ecol 29:201–208

Rasse DP, Rumpel C, Dignac MF (2005) Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. Plant Soil 269:341–356

Regato P, Salman R (2008) Mediterranean mountains in a changing world: guidelines for developing actions plans. IUCN

Rigolot E, Lambert B, Pons P, Prodon R (2002) Management of a mountain rangeland combining periodic prescribed burnings with grazing: impact on vegetation. In: Trabaud L, Prodon R (eds) Fire and biological processes. Backhuys Publishers, Leiden, pp 325–337

Rosset M, Montani M, Tanner M, Fuhrer J (2001) Effects of abandonment on the energy balance and evapotranspiration of wet subalpine grassland. Agr Ecosyst Environ 86:277–286

Roura-Pascual N, Pons P, Etienne M, Lambert B (2005) Transformation of a rural landscape in the Eastern Pyrenees between 1953 and 2000. Mt Res Dev 25:252–261

Ruess RW, Hendrick RL, Bryant JP (1998) Regulation of fine root dynamics by mammalian browsers in early successional Alaskan taiga forests. Ecology 79:2706–2720

Saccone P, Morin S, Baptist F, Bonneville JM, Colace MP, Domine F, Faure M, Geremia R, Lochet J, Poly F, Lavorel S, Clément JC (2013) The effect of snowpack properties and plant strategies on litter decomposition during winter in subalpine meadows. Plant Soil 363:215–229

Sanz-Elorza M, Dana ED, Gonzalez A, Sobrino E (2003) Changes in the high-mountain vegetation of the central Iberian Peninsula as a probable sign of global warming. Ann Bot-London 92:273–280

Shaw MR, Harte J (2001) Control of litter decomposition in subalpine meadow-sagebrush steppe ecotone under climate change. Ecol App 11:1206–1223

Smith P (2004) How long before a change in soil organic carbon can be detected? Glob Change Biol 10:1–6

Stöhr D (2007) Soils—heterogeneous at a Microscale. In: Wieser G, Tausz M (eds) Trees at the upper limits. Springer, Dordrecht, pp 37–56

Smith DL, Johnson L (2004) Vegetation-mediated changes in microclimate reduce soil respiration as woodlands expand into grasslands. Ecology 85:3348–3361

Smith EL (2008) Potential longterm impacts of livestock introduction on carbon and nitrogen cycling in grasslands of Southern South America. Glob Change Biol 12:1267–1284
Teepe R, Brumme R, Beese F (2001) Nitrous oxide emissions from soil during freezing and thawing periods. Soil Biol Biochem 33:1269–1275
Tierney GL, Fahey TJ, Groffman PM, Hardy JP, Fitzhugh RD, Driscoll CT (2001) Soil freezing alters root dynamics in a northern hardwood forest. Biogeochemistry 56:175–190
Waldrop MP, Firestone MK (2004) Microbial community utilization of recalcitrant and simple carbon compounds: impact of oak-woodland plant communities. Oecology 138:275–284
Walker MD, Walker DA, Welker JM, Arft AM, Bardsley T, Brooks PD, Fahnstrock JT, Jones MH, Losleben M, Parsons AN, Seastedt TR, Turner PL (1999) Long-term experimental manipulation of winter snow regime and summer temperature in arctic and alpine tundra. Hydrol Process 13:2315–23130
Wardle DA, Bardgett RD, Klironomos JN, Setälä H, van der Putten WH, Wall DH (2004) Ecological linkages between aboveground and belowground biota. Science 304:1629–1633
Wipf S, Sommerkorn M, Stutter MI, Jasper Wubs ER, van der Wal R (2015) Snow cover, freeze-thaw, and the retention of nutrients in an oceanic mountain ecosystem. Ecosphere 6, art. 207
Xie ZB, Zhu JG, Liu G, Cadisch G, Hasegawa T, Chen CM, Sun HF, Tang HY, Zheng Q (2007) Soil organic carbon stocks in China and changes from 1980s to 2000s. Glob Change Biol 13:1989–2007
Zhao W, Chen SP, Lin GH (2008) Compensatory growth responses to clipping defoliation in Leymus chinensis (Poaceae) under nutrient addition and water deficiency conditions. Plant Ecol 196:85–99
Zollinger B, Alewell C, Kneisel C, Meusburger K, Gärtner H, Brandová D, Ivy-Ochs S, Schmidt MWI, Egli M (2013) Effect of permafrost on the formation of soil organic carbon pools and their physical-chemical properties in the Eastern Swiss Alps. CATENA 110:70–85
Zornoza R, Guerrero C, Mataix-Solera J, Scow KM, Arcenegui V, Mataix-Beneyto J (2009) Changes in soil microbial community structure following the abandonment of agricultural terraces in mountainous areas of Eastern Spain. Appl Soil Ecol 42:315–323

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter’s Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter’s Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.