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Challenges facing alpine/ mountain grasslands

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1 Introduction

Mountain grasslands are the basis of a site-specific, locally based livestock production in a large part of the grassland area of the temperate zone. This chapter first outlines the site factors characterising mountain grasslands and the societal factors connected to them (Fig. 1). It then addresses the specificities of mountain grassland production in terms of yield and forage quality and links them to grassland-based animal production. Finally, it discusses relevant trade-offs between productive and environmental aspects with a focus on wildlife interaction and the expression of ecosystem services. Throughout this chapter, the mountain chain of the Alps, stretching from East to West from France to Slovenia and crossing eight countries, as well as the Scandinavian Mountains, running through the Scandinavian Peninsula, will serve as a primary case study. However, several issues addressed in this context are shared with other mountain areas characterised by comparable climatic and topographic

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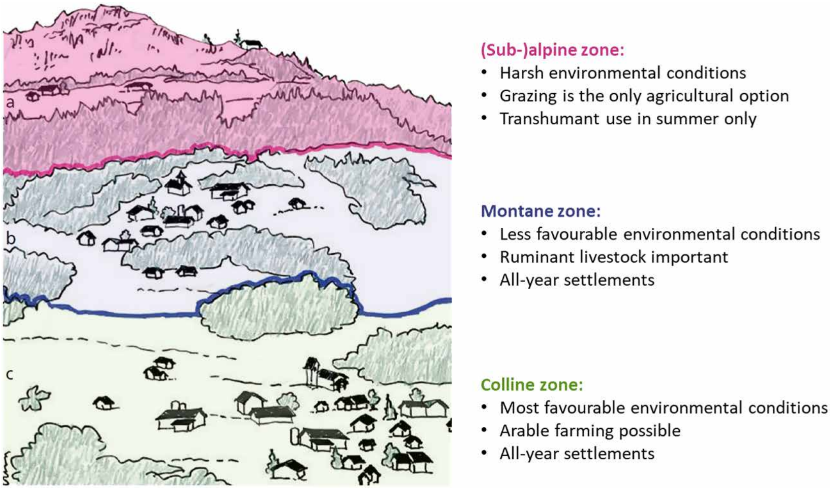

Figure 1 Type of agricultural activities depending on the altitudinal zone in the Alps (based on the artwork by U. Kaufmann, used with permission from Lauber et al. (2013), and modified by the authors).

conditions, e.g. other mountain chains in Europe like the Apennines or the Dinarides in Southern Europe, the Carpathians in Central Europe or the Pyrenees in Western Europe, as well as with other extra-European mountain chains.

2 Topography and climate

The dynamics and adaptability of grasslands to different site conditions, which vary significantly in mountain areas, are due to the diverse botanical composition and the interspecific interactions (Frei et al., 2014). As long as there is an equilibrium in terms of nutrient balance and coherence between site potential and management intensity, the adaptation of the plant community to the site conditions and to the management creates a stable and resilient ecosystem embedded in a sustainable circular economy (Pötsch et al., 2006). In mountain areas, abiotic site factors change on a comparatively small scale, resulting in a wide variety of utilisation forms and intensities in grasslands (Pötsch, 2012). Grassland farming in mountain areas is, therefore, generally small-scaled and strongly characterised by the following site factors:

- topography (elevation, slope, aspect);
- climate (temperature, precipitation, insolation); and
- soil (pH, depth, organic matter content, nutrient availability, texture, porosity).

Elevation causes a decrease in temperature according to a linear gradient, which largely determines the climatic conditions affecting grasslands management (Fig. 2a). Only through appropriate temperatures and radiation, assimilation processes are maintained and development phases such as germination or generative growth initiated (Keller et al., 1997). With increasing elevation, decreasing temperature reduces the duration of the growing season, thus limiting the number of growth cycles being potentially harvested, with decreasing performance in terms of forage yield. Slope (Fig. 2b) and aspect (i.e. the orientation faced by a terrain surface) usually change on a small scale, affecting the microclimate, which primarily depends on radiation and heat balance. This further increases the spatial variability of productivity and, in some cases, makes management considerably more difficult. Steeper areas also limit or complicate mechanisation and increase costs and workload, because of the need of special machineries or even manual work. Grazing in alpine grasslands requires livestock adapted to e.g. climatic conditions, terrain and wildlife, especially in steeper terrain. Light-weighted, robust breeds are particularly suited, as they are able to climb steep slopes and exert less pressure on the ground, thereby reducing the negative effects of trampling and the risk of erosion. The effect of aspect can be strong in mountain areas: south-facing areas experience an earlier start of the growing season due to longer and more intense radiation, causing earlier snowmelt and higher temperature but can be susceptible to summer drought spells due to higher evapotranspiration (Hua et al., 2022). Due to the mentioned environmental

a) Impact of increasing elevation = decreasing temperature on...		b) Impact of increasing slope on...		c) Impact of increasing remoteness on...	
Productivity	↓	Costs per product unit	↑	Conflicts with wildlife	↑
Duration of growing season	↓	Erosion	↑	Abandonment and encroachment	↑
Evapotranspiration and drought risk	↓	Physical workload	↑	Depopulation and missing generation turnover	↑
Duration of winter-feeding period	↑	Agricultural options	↓	Dependence on public payments	↑
Small-scale variability and abundance of specialised species	↑	Ease of mechanisation	↓	Communal ownership	↑
(Drinking) water supply	↑	Soil depth	↓	Infrastructure availability	↓

Figure 2 Impact of increasing mountain character of the environment (increasing elevation strongly correlated with decreasing temperature as well as increasing slope and remoteness) on different aspects of grassland farming, based on expert guesses of the authors. Upward pointing arrows indicate an increase, downward pointing arrows a decrease. The thickness of the arrows express the magnitude of the impact.

constraints, mountain grassland farming can only be maintained if there is a social interest and a political will to financially compensate these disadvantages or through innovative business models in which the price of the animal products economically rewards farmers for their added value contributions in delivering the ecosystem services provided by mountain grasslands (van den Pol-van Dasselaar et al., 2021). To this end, specially tailored subsidy models are already put into practice in various countries.

Physical and chemical soil properties, in conjunction with biotic factors, significantly influence the productivity of mountain grasslands. Intact soil life is essential for the mineralisation of organic material and the associated provision of nutrients in a form available to plants. The farmer can support productivity through fertilisation. In contrast, the consequences of agricultural activities, such as compaction due to mechanical stress, can impair soil fertility. In principle, soil type, nature, structure and depth are responsible for soil nutrient, water, air and heat balance (Keller et al., 1997). In former times, in a context of a subsistence economy, arable crops were widely diffused on a very small scale in mountain areas at the cost of huge amounts of working time and physical work, but this is no longer economically viable in the current context. Compared to arable land in favourable locations, permanent grasslands in mountain areas usually have lower soil fertility, in combination with topographical and climatic constraints. If basic requirements allowing for the mechanisation of ploughing are not met (e.g. where the slope exceeds about 20%), grassland and livestock farming are the only possible forms of agricultural utilisation in mountain regions. Moreover, grasslands provide several ecosystem services related to the soil. For example, permanent grasslands stabilise soil structural characteristics, prevent soil erosion, increase the organic matter content and improve water-retention capacity (Milazzo et al., 2023a,b; Saha and Kukal, 2015; Zhao et al., 2020b). Especially in connection with climatic changes and the trend towards drier conditions, the buffering function of the soil for a sufficient supply of nutrients and water is of great importance.

As for all crops, the climate and its interaction with topography and soil significantly influence grasslands. In high mountain regions, the growing season is short and plant growth is limited. The growing season depends less on the photoperiod itself than on the closely related annual temperature cycle and duration of snow cover (Filippa et al., 2019). Grassland vegetation is less demanding than other crops in terms of temperature but largely depends on precipitation as the primary factor determining grassland productivity, particularly in ecosystems that are either water-limited or under heath stress. Although solar radiation and temperature also affect productivity, their impact is secondary to the critical role of precipitation in driving grassland net primary productivity (Zhao et al., 2020a; Chen et al., 2023). Above all, a sufficient moisture at the beginning of the vegetation period is crucial for a high yield of the first growth cycle in spring. The Alps are particularly vulnerable to climate change and have already experienced twice as much warming since the beginning of the industrial age compared to the global average (Pepin et al., 2022; Kotlarski et al., 2023). This warming affects natural ecosystems and the cultivated landscape. Climate projections for the coming decades show an intensified trend towards further increases in mean temperature and unevenly distributed precipitation (IPCC, 2022). A decrease in moderate rainfall and an increase in heavy rainfall are already leading to recurrent intense drought spells in combination with high temperatures at various times of the year (Trnka et al., 2011; Pötsch et al., 2014). Although temperate grassland species have been shown to be largely robust and resilient against drought (Deléglise et al., 2015; Hofer et al., 2016), the uncertainty of forage production for farmers and the related need for purchasing off-farm forage jeopardises the profitability and the persistence of mountain grassland farming in the long term (Schaumberger et al., 2022). Because of the ongoing climate change, an increase in biomass provision is expected at low elevation in the Pre-Alps (i.e. the foothills at the base of the Alps), while a decrease in biomass provision is expected on the southern side of the Alps (Jäger et al., 2020). Moreover, a shift in the duration of the growing season through an earlier start and a later end is expected (Möhl et al., 2022; Wang et al., 2020).

Topography, soil and climate directly influence the dynamics and resilience of grassland ecosystems (Sebastià, 2004; Schirpke et al., 2017). Effective management and adaptation strategies must consider these complex relationships to ensure the sustainable utilisation of grasslands under a changing climate (Vogel et al., 2012; Schils et al., 2022). To a certain extent, the botanical composition can adapt to drier conditions, with drought-tolerant grass species and deep-rooted legumes or herbs increasing their proportion (Sanaullah et al., 2014; Tello-Garcia et al., 2020). However, active adaptation measures are required. This concerns the management (fertilisation and utilisation times, irrigation, etc.) and active adaptation of the plant communities through systematic weed control and reseeding with drought-tolerant forage species and cultivars within species.

3 Socioeconomic aspects

The topography of mountains increases the cost of travel from one point to another. This seemingly obvious characteristic has tremendous consequences for mountain livelihood systems and land use (Figs. 2b and 2c). As a first consequence, more energy or time is needed to reach a certain spot in mountain terrain than in a flat area (ESPON, 2019: Maps 5–7). This poorer accessibility increases transport costs of harvested biomass from field to farm and of manure and fertiliser from the farm to the field. As a consequence, the labour needs and the costs of forage production per area unit increase as a curvilinear, convex function of slope. If the costs of forage production are computed on the forage yield unit, the costs are a function of the interaction of slope and elevation and rise very rapidly as both factors increase (Peratoner et al., 2017; Peratoner et al., 2021). As slope steepness and remoteness of the grassland areas increase, it is therefore more advantageous to graze (i.e. lead animals to forage) than to feed in-house (bring forage to the animals). Grazing in remote places requires appropriate herding of these animals which is, due to the higher costs of travel, difficult for the owner of the animals himself besides work at the farmstead. Therefore, additional persons (e.g. family members, villagers or outsiders) are engaged during summer for the herding task for centuries in mountain areas (Calabrese et al., 2014) and the animal owner has time for work at the farmstead.

The low accessibility of mountain grasslands leads to a second particularity: the ‘common property rights’, which are frequent in mountain regions (Landolt and Haller, 2015; Galan et al., 2022). Communal ownership and communal organisation of work have several advantages in mountain grazing systems over private ownership, namely economies of scale in the workload, the hiring of external personnel and investments to access and housing. On the other hand, communal systems need a higher degree of agreement to ensure a fair and sustainable use of natural resources and complex decision processes for the adaptation to current and future changes (Baur and Binder, 2013).

Recent decades have seen important transitions in demographic and agricultural structures in mountain areas. In the Alps, there are strong regional differences, but several general trends can be observed: The overall population in the Alps (as defined by the perimeter of the Alpine Convention) increased by 7.8% from 1994 to 2004, but there are strong local differences among the 6000 alpine municipalities (Zanolla et al., 2007). In general, well-connected alpine towns are strongly gaining population at the expense of remote agricultural villages. Municipalities primarily devoted to agriculture are transformed into areas devoted to both agriculture and tourism or dominated by tourism only (Bätzing et al., 1996). The number of farms decreased by 35% between 1980 and 2000 (Streifeneder et al., 2007) due to a lack of successors (Flury et al., 2012) and this process is ongoing. In parallel with the reduced agricultural labour force, the importance of agriculture in municipal decision-making processes decreases and more importance is given to other stakeholders (e.g. tourism and power production).

Since the total agricultural area decreased less than the number of farms (by 7.6%; Flury et al., 2012), the surface area managed per farm increased. However, managing larger units and more land requires investments in infrastructure and machinery. These investments, in turn, necessitate the specialisation of animal production (unified herds) and forage conservation (silage or hay) as well as a rationalisation of work processes (including mechanisation). This has consequences for the livelihood system of mountain farmers: a recent study in a Swiss mountain region found that farmers increased commercial and administrative contacts at the expense of social contacts within their families and with friends (Junquera et al., 2022). This demonstrates the transition of family-run farms towards professional agri-food enterprises.

The professionalisation and rationalisation of farm operations have several consequences on mountain grassland use and maintenance. Forage production is concentrated on flat and productive sites, manageable with machinery (Marini et al., 2009). High productivity of livestock allows comparable output at lower numbers of heads leading to a substantial drop in animal numbers in certain regions (Battaglini et al., 2014). However, highly productive animals are less suited to graze low-productive and steep mountain pastures and are hence supplemented with concentrates or herded on the best sites only (van Dorland, 2007). Finally, the lower number of people employed in agriculture reduces the available labour force for manual work such as fencing or pasture maintenance (Baur et al., 2014).

4 Forage production

Grassland productivity in mountain areas is limited in the first instance by the decreasing duration of the growing season and heat balance with decreasing temperatures (Jäger et al., 2020). At high elevations, the period of indoor feeding far exceeds the grazing period. The limited duration of the growing season results in a need for harvesting and storing forage for the winter months. Especially under relevant topographic constraints, this leads to an additional burden in terms of workload and investments for special machineries and facilities (e.g. barn-drying systems) to perform this task.

Grassland management is closely linked to site factors; site-adapted management aims at taking them into account and establishes a robust and resilient utilisation system, which is able, in the long term, to cope with the climatic challenges of the mountain environment and to ensure a balance in terms of nutrients. Therefore, in mountain grasslands, the focus does not lie on the short-term maximisation of yields through the intensive use of external inputs, but on ensuring stable yields and high forage quality in line with the principles of circular agriculture. In mountain regions, shallow soils, steep slopes, and extreme weather events with significant annual fluctuations are often the main challenges. Climate change results in extended vegetation periods (Bellini et al., 2023) and opens up new utilisation possibilities but also requires adapted management to retain high forage quality. Increased management intensity through more cuts or intensive grazing, along with high fertiliser application, leads to higher evapotranspiration but better water-use efficiency. This applies above all to fertilisation, as this significantly enhances biomass production (Rose et al., 2012). Therefore, intensification should only occur in areas with sufficient water availability. Flexibility in management is essential to respond to annual fluctuations, e.g. by reducing the mowing frequency in unfavourable years.

Biodiversity is crucial for the ecological stability of mountain grassland habitats and their agricultural production, as biodiverse systems are expected to be more resilient, which is especially important in areas of high fluctuation in environmental conditions. Particularly, on less productive sites, it is essential to maintain or even promote plant and animal diversity to counteract the general loss of diversity observed in grasslands in the last decades (Isselstein, 2018).

Also, the economic viability of site-adapted farming methods requires careful evaluation. The direct production functions and the ecological and socio-economic functions of grassland production require equal consideration. Public payments and incentives for farmers who adopt sustainable practices are essential for implementing this approach. Nevertheless, many grassland areas in Europe, usually including the more favourable areas in the Alps, face a mismatch of site potential and management intensity due to overemphasising the production function. This focus often leads to disproportionate intensification – a practice that undermines the sustainability of these regions and diminishes the multifunctionality of permanent grasslands (Schils et al., 2022). Management intensity that exceeds the site optimum can lead to degeneration of the sward, whereby important species disappear. Undesirable, opportunist species often colonise the resulting gaps. Additionally, fertilisation is subject to stringent regulations within the European Union. Consequently, uniformly high nutrient levels across large-scale areas are not feasible, necessitating a differentiated approach to management intensity.

Conversely, many sites, particularly remote areas and those with challenging topographical conditions, including highly diverse habitats with a rich species variety, are subject to excessive extensification or abandonment. The resulting loss of valuable graduated agricultural mosaics leads to both agriculturally and ecologically detrimental consequences. The abandonment of utilisation leads to the establishment of tall grasses and perennial woody species, which increasingly reduce the biodiversity of moderately managed meadows and pastures (Dengler and Tischew, 2018). Another adverse effect of the reduction in utilisation is the increasing evapotranspiration in alpine grasslands, especially when the abandoned areas reach a higher leaf area index (LAI) than that of pastures (Inauen et al., 2013). Moreover, the additional water consumption following bush encroachment with alder species leads to a reduced rate of deep percolation and thus reduces the total amount of water available in a catchment area (van den Bergh et al., 2018).

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Site-adapted management strives to create a resilient and comprehensive agricultural system that combines production goals with ecological and socio-economic functions. The aim is to recognise the site's potential and adjust management intensity to achieve stable yields that are resilient to biotic and abiotic stress factors, rather than focussing solely on short-term maximum yields. This requires a deep understanding of local conditions and flexible, forward-looking planning and implementation of management practices.

A further challenge is the evaluation of forage yield and quality. Its assessment is a challenging task in mountain areas, due to the small-scaled variability of topography and the lower predictability of the meteorological conditions. It requires an in-depth understanding of the many influencing factors and their complex interactions. The site conditions – including soil, climate and topography – form the basic framework for agricultural utilisation and are the starting point for all further management-related decisions. Management methods must be carefully selected and implemented in line with these natural conditions. The type and intensity of utilisation play a central role in ensuring stable yields and high forage quality. This includes practices such as mowing for hay or silage, grazing or combining both, coupled with fertilisation tailored to the site and utilisation aligned with maintaining closed nutrient cycles and avoiding both over-fertilisation and under-fertilisation.

The botanical composition of the sward, as a direct result of site factors and management, can be positively influenced by targeted interventions such as reseeding or weed control. To ensure long-term successful grassland management, continuously monitoring growth dynamics and regularly evaluating yields and forage quality are crucial.

Knowledge of grassland biomass yield is crucial for optimising management, but it is also a challenging task. Despite its importance, this data remains mostly unknown to farmers. In contrast, forage quality is assessed more frequently. However, the laboratory analysis of forage samples, a standard method for precisely determining the chemical composition, does not allow for timely adjustments in grassland management since it is only feasible post-harvest. Indirect indicators such as sward height and botanical composition of the vegetation provide valuable information even during the growth phase (Peratoner and Pötsch, 2019). In addition to simple methods, such as a scale, sward stick or a pasture plate meter (Murphy et al., 2021; Stewart et al., 2001), advanced techniques, such as creating 3D models using drone imagery (Bazzo et al., 2023) or ultrasonic sensors (Fricke et al., 2011), provide detailed insights into the yield situation. The phenology of dominating species also enables the estimation of forage quality; therefore, tabulated values based on empirical data deliver useful information in this sense (Resch et al., 2006; Daccord et al., 2007). The combination of automatically retrieved topographic and meteorological data with information about the management and a simple characterisation of the sward type provided by the users allows a further improvement of the estimate of forage quality by means of statistical predictive models driven by Growing Degree Days and other complementary information (Peratoner et al., 2016).

Modern technologies and innovations are increasingly important in grassland management, particularly in recording and analysing growth characteristics, including the start of the growing season (Dujakovic et al., 2024), cut detection (Dujakovic et al., 2025; Holtgrave et al., 2023; Schwieder et al., 2022; Siegmund et al., 2019; Taravat et al., 2019; Watzig et al., 2023) and yield (Castelli et al., 2023) and forage quality estimation. Combined with algorithms and artificial intelligence, satellite images and weather data provide valuable information on cut frequency and real-time yield forecasts. These technological advances enable comprehensive monitoring, even on small-structured inner-alpine meadows and pastures, and contribute significantly to the optimisation of grassland management.

5 Animal production

The advantage of ruminants is their ability to digest fibrous plant material and convert it into high-quality food for human consumption in terms of protein and energy. Thus, ruminants can be fed with forage from areas not suitable for the production of e.g. grain and other crops directly suited for human nutrition. In this way, mountain grasslands contribute to meeting the increasing food demand without competing with more efficient agricultural forms of food production. Depending on the length of the growing season, the animals can harvest more than 50% of their annual feed from mountain or alpine pastures (Bunger et al., 2018) which makes these areas highly relevant. In mountain areas, this often happens by altitudinal transhumance. Following the altitudinal gradient from the valley to alpine areas and the respective gradient of phenological advance, the animals graze plants at early phenological stages of high quality over weeks or even months. Due to this upward movement, the animals use the pastures at their optimum in terms of forage quality.

Food produced in mountain areas is perceived positively and considered sustainable (Hersleth et al., 2012). Sensitive consumers, however, may complain about off-odours and off-flavours and a variation in meat quality (Prache et al., 2022). Eating quality of meat is positively related to intramuscular fat content (Pannier et al., 2014). As an animal gets older, the muscle-to-fat proportion changes towards more fat and less muscle, which from a sensory point of view may be positive. Moreover, the highly diverse composition of grasses, shrubs, herbs and other species containing secondary metabolites may influence the taste of milk and meat, which are thus less uniform than food produced on lowland pastures (Ådnøy et al., 2005) or based on concentrate (Lind et al., 2009).

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Some secondary metabolites, such as tannins, saponins, polyphenol oxidase, flavonoids and essential oils, may improve the fatty acid composition to a larger content of polyunsaturated fatty acids (Girard et al., 2016; Campidonico et al., 2016).

Environmental conditions of mountain grasslands can pose a challenge for grazing animals. Thus, site-adapted livestock is mandatory to cope with steep slopes, harsh climate and low forage quality at high elevation (Pauler et al., 2020a, b). Generally, local breeds seem to be well adapted to alpine vegetation systems (Willems et al., 2013). However, higher yielding dairy cows or goats depend on higher quality forage and additional concentrate (Sturaro et al., 2013) and may alter vegetation composition in an undesired way in the long term (Pauler et al., 2019). For highly productive breeds, pastures at high elevation are of less importance, as they may compromise both milk yield and animal health. Site-adapted management means matching livestock productivity level and pasture management intensity to the specific site conditions. However, due to the intensification of the farming structure in Europe, fewer animals ensure the same production level, as the production per animal increases. Therefore, more off-farm feed (including concentrate) is imported from lowland areas where grass yield and forage quality are higher and mechanisation is easier. Consequently, there is less livestock utilising alpine and mountainous pastures.

For instance, in the traditional production of summer milk in Norway, dairy cows are moved from the lowland farms to mountain farms for 2 months during summer. Today, the production system is endangered as the productivity of the cows is increasing. The pasture quality is insufficient, even when feeding additional concentrates to maintain the high yield of the cows. Those farms still producing summer milk are those that primarily have less intensive production in the lowland during the rest of the year. Native breeds (e.g. Sider-trønder Nordlandsfe) are more suited for the production of summer milk than high-yielding dairy cows (Norwegian Red Cattle). The native animals are smaller with lower milk yield and thus demand less feed. As the number of summer farms decreases, more areas are left abandoned with shrub encroachment as a result. The quality of the pasture decreases, and this makes it less likely that farmers will start summer farming again (Bele et al., 2018). A similar development is found in the Alps. Unique dairy and meat products produced in mountainous grasslands are often certified with a Protected Designation of Origin (PDO) label. Products must meet high quality to be certified, and the certification is followed by strict regulations for the production system and requires foresight for authentication and traceability criteria (Coppa et al., 2017). The distribution channels for these products often fall outside the established distribution channels and often must be developed alongside the products by the farmers themselves or smaller cooperatives. However, if successful, higher prices can be realised in the market due to the unique character of these products.

6 Interaction with predators

Pasture-based farming systems in mountain regions are threatened by an increasing number of large carnivore predators. Wolves are a commonly found predator in the Scandinavian mountains and the Alps. The recent natural recolonisation of many European areas by wolves has increased conflicts with humans (Boitani and Linnell, 2015). Conflicts arise particularly in regions where farmers are no longer used to protecting their livestock due to the absence of predators over centuries. There, livestock often is left grazing unattended and unprotected, even at night. Reducing conflicts due to predation on livestock therefore requires changes in farming practices and the adoption of protection methods (Dalmasso et al., 2011; Boitani and Linnell, 2015). In fact, damage compensation alone fails to reduce the conflicts between livestock farming and carnivores (Dalmasso et al., 2011). Sheep and goats are the livestock species most frequently killed by wolves in Europe (Reinhardt et al., 2012), but predation on cattle also occurs (Dalmasso et al., 2011). Additionally, lynx, wolverine, bears and eagles are seen in Scandinavia and the Alps. The predators predate in different ways and at different times of the grazing season. Preventive measures such as guarding dogs, early gathering of livestock and mortality collars are being used (Hansen et al., 2019). When farmers lose as much as 30–50% of their flock to predators, the production is endangered. While some farmers give up, others change their type of livestock to animals less exposed to predators (e.g. replacing sheep with beef cattle). Successful coexistence of large carnivores and humans depends on the effective mitigation of their impact on humans, especially through livestock predation. It is therefore essential for relevant stakeholders like livestock owners, conservation practitioners or carnivore managing authorities to know the effectiveness of interventions intended to reduce livestock predation by large carnivores: keeping livestock in enclosures, guarding or livestock guarding dogs, predator removal and using visual or auditory deterrents to frighten carnivores. Literature shows a general lack of scientific evidence of the effectiveness of any of these interventions: some interventions reduced the risk of depredation whereas other interventions did not result in reduced depredation. For example, livestock enclosures and livestock guarding (either by humans or dogs) generally appear to be effective interventions for protecting livestock from carnivores, but the effect of interventions is context-dependent and appears to vary with how well the actual problem is targeted (Eklund et al., 2017). Visual or auditory deterrents over time become familiar features in the wolves' environment, and as a consequence, their effectiveness decreases. For research, there is an urgent need to conduct studies of intervention effectiveness to support for the implementation of policies and strategies aiming at reducing conflicts between carnivores and livestock.

7 Ecosystem services

Especially in the valleys, the production of forage for ruminants is an important ecosystem service of mountain grasslands. Even at higher elevations, pastures contribute substantially to ruminant nutrition, although productivity decreases with elevation. In Switzerland, for instance, the transhumant summer pastures feed 10% of Swiss livestock while covering one-third of agricultural land (Stettler and Probst, 2023). As multifunctional ecosystems, mountain grasslands offer a broad bundle of services to society beyond food production, which become more important at higher elevations.

Mountain grasslands offer numerous cultural services, and the transhumant summer farming is even part of UNESCO's representative list of the intangible cultural heritage of humanity. For millennia, transhumant grazing of high-elevation areas has shaped mountain farming societies (Hafner and Schwörer, 2018). They developed an annual cycle in which the date of driving livestock up and down the mountain represents turning points setting the pace of life in the valley as well as on the mountain farms. Traditional costumes and rituals, like choosing the most beautiful cow in autumn, are closely related to mountain grazing traditions.

Grazing shaped not only culture in mountain areas but also the ecosystems themselves: over millennia, livestock opened forested or shrub-encroached areas by grazing, thereby creating semi-natural open grasslands and lowering the tree line. Grazing, hay cutting for winter forage and deforestation for firewood and timber accelerated this process and created large, open landscapes at the valley floor. The anthropogenic, extensive grasslands created by livestock farming host outstanding biodiversity (Kampmann et al., 2008). They are arks of diversity in times of declining species richness. Moreover, these wide and open landscapes are key for almost all types of mountain tourism (Parente and Bovolenta, 2012), including agritourism as well as hiking, mountain biking or skiing, and thus are the precondition of employment in the mountain tourism sector. Finally, mountain grasslands contribute to climate change mitigation by their mostly overlooked carbon sequestration potential (Ward et al., 2014) and enhance hazard protection. In this respect, grasslands provide better flood prevention and erosion mitigation and are almost comparable in these terms to forests (Milazzo et al., 2023b).

Multifunctional mountain grasslands and the ecosystem services they provide depend on continuous agricultural management. However, there is a two-sided trend in modern agriculture threatening the multifunctionality (Fig. 3): intensification and extensification, both leading to a loss of multifunctionality of ecosystem services (Tasser and Tappeiner, 2002).

On the one hand, the more favourable mountain grasslands are managed in increasing intensity. Farmers enhance productivity, for instance, by using

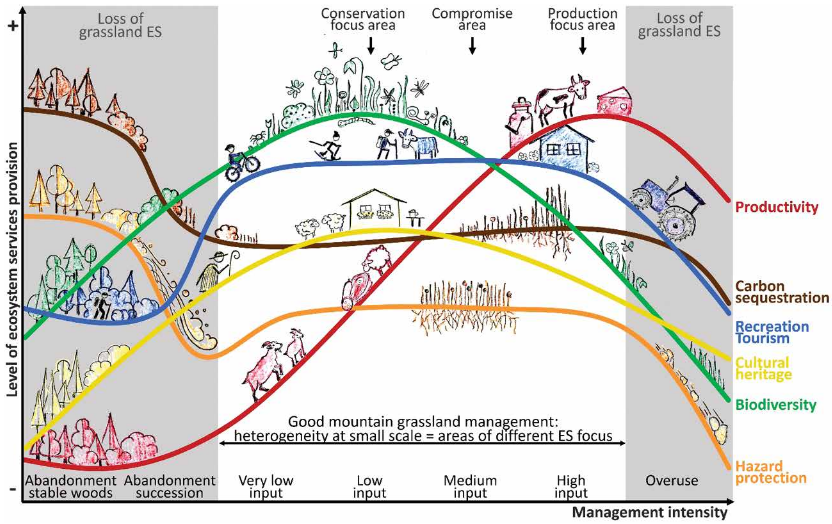

Figure 3 Change of the level of ecosystem services (ES) provision along a management intensity gradient, including abandonment and overuse at the lower and upper end of the gradient, based on expert guesses of the authors (artwork by Caren Pauler). As different ecosystem services peak at different management intensity levels, trade-offs are apparent.

machinery, applying fertilisation and by grazing more output-oriented livestock. Intensification causes uniformity of grasslands by promoting only a few highly competitive generalist species. Thus, intensified grasslands lose their specific biodiversity. Pastures grazed by a higher number of more productive, heavier animals suffer from increased trampling pressure (Pauler et al., 2019, 2020a) causing open and compacted soils. Consequently, intensification leads to less soil stability, more erosion, less water-holding capacity and less flood prevention.

On the other hand, if less favourable grasslands cannot be managed to cover costs, they are managed at very low grazing pressure or are even completely abandoned. This applies especially to steep and rocky pastures of shallow soil, low productivity and little infrastructure. As a result, succession begins, and in the long term, grasslands are overgrown by forest (below the natural tree line) or shrubs (above the natural tree line) and the majority of mountain grassland ecosystem services are lost (Prangel et al., 2023; Schirpke et al., 2020). For instance, cultural values as well as cheese and meat production are built on grasslands. Moreover, open grasslands and wood-grassland mosaics are generally more attractive than dense woodlands (Soliva et al., 2010) for tourism as well as for locals and provide a much better protection from forest fires (Conedera et al., 2024). However, avalanche protection (Mainieri et al., 2020) and carbon sequestration in above-ground biomass may benefit from reforestation. Concerning shrub encroachment, one shrub species has to be emphasised in particular due to its rapidly increasing distribution and multifarious impairment of ecosystem services: The green alder (*Alnus viridis*) is the most common invasive shrub in the European Alps (Pauler et al., 2022). It emits nitrous oxide, a highly potent greenhouse gas (Smith et al., 2021) probably negating the carbon sequestration in wood biomass. In general, dense shrub stands host much lower biodiversity than open mountain grasslands or patchy wood-grassland mosaics, but for grasslands encroached by *Alnus viridis*, the decline of diversity is much stronger than for other shrubs (Zehnder et al., 2020). Moreover, due to its high competitiveness, *A. viridis* even hinders forest reestablishment and the realisation of forest-related ecosystem services.

In summary, it is impossible to maximise all ecosystem services in the same places due to strong trade-offs among them, but the high small-scale variability of mountain grasslands allows for the realisation of a multitude of services in proximity. Overuse or underuse leads to a loss of most ecosystem services; only above-ground carbon sequestration and hazard protection benefit from abandonment and wood succession. However, during the transition phase – which can last for decades at high elevations – long, bent-over grass not foraged by animals can even exacerbate the risk of avalanches. During the last centuries and decades, additional functions of mountain grasslands have emerged, causing additional conflicts. For instance, the positive aspects of tourism, such as employment and improved infrastructure, come along with land-use conflicts, dangerous interactions between tourists and herd guard dogs, and a degeneration of mountain traditions into sheer touristic events. Moreover, in view of climate change, there is a legitimate interest in green energy produced in mountain areas. This, however, causes additional pressure on grasslands, which have been identified as ideal places for solar parks, wind farms or reservoirs for hydroelectric power. Today, mountain grasslands face the challenge of incorporating these new services while maintaining their productivity, species richness and their outstanding cultural value.

8 Future trends in research

Based on the current situation described in this chapter and the ongoing changes, the following research topics emerge as particularly relevant:

- Adaptation of mountain farming systems to changing climate, including the selection of plant species/varieties and livestock species/breeds adapted to mountain conditions and exploration of the genetic basis.
- Establishment of systems making use of the potential of digitalisation and technological advances to increase the efficiency of mountain farming

systems and to decrease the costs of production under disadvantaged conditions.

- Development of approaches to solve or mitigate the conflicts of interest between agricultural production, tourism, predators and energy production.
- Development and evaluation of sustainable mountain farming systems (with regard to ecological, economic and social dimensions).

9 Where to look for further information

In most countries (or regions within countries), including mountainous areas, associations dealing with grassland management in a mountain environment have been established. They provide at the local level a valuable source of information concerning relevant topics in the foreground and the results of research activities to address emerging issues, with a special focus on knowledge transfer. As their activities usually foresee the interaction of both scientists and practitioners, they contribute to effectively bridge the gap between research and practice. As an example, we mention here SoZooAlp (Società per lo Studio e la Valorizzazione dei Sistemi Zootecnici Alpini) in Northern Italy (https://www.sozooalp.it/), AGFF (Swiss Grassland Society) in Switzerland (https://www.agff.ch/), ÖAG (Österreichische Arbeitsgemeinschaft für Grünland und Viehwirtschaft) in Austria (https://gruenland-viehwirtschaft.at) and NLR (Norsk Landbruksraedgiving) in Norway (https://www.nlr.no/). The FAO-CIHEAM Mountain Pastures Sub-Network is an international platform for exchange between research institutions operating in mountain regions.

10 References

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