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Historical trajectories in land use pattern and grassland ecosystem services in two European alpine landscapes

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Abstract

Land use and spatial patterns which reflect social-ecological legacies control ecosystem service (ES) supply. Yet, temporal changes in ES bundles associated with land use change are little studied. We developed original metrics to quantify synchronous historical variations in spatial patterns of land use and ES supply capacity, and demonstrated their use for two mountain grassland landscapes. Consistent with other European mountains, land use dynamics from the nineteenth century until the mid-twentieth century resulted in increased landscape heterogeneity, followed by homogenisation. In the persistently grassy landscape of Lautaret in France, landscape multifunctionality—the provision of multiple ES—coincided with greatest landscape heterogeneity and within-patch diversity in ecosystem services in the 1950–1970s. In the more complex Austrian landscape, where since the nineteenth century intensive production has concentrated in the valley and steep slopes have been abandoned, grassland landscape-level multifunctionality and spatial heterogeneity across grasslands have decreased. Increasing spatial heterogeneity across grasslands until the 1970s was paralleled at both sites by increasing fine-grained spatial variability for individual ES, but subsequent landscape simplification has promoted coarse-grained ES patterns This novel analysis of landscape-scale turnover highlighted how spatial patterns for individual ES scale to multiple grassland ES, depending on the nature of land use spatial variability. Under current socio-economic trends, sustaining or re-establishing fine-grained landscapes is often not feasible, thus future landscape planning and policies might focus on managing landscape and regional-scale multifunctionality. Also, the trends towards decreasing cultural ES and increasing regulating ES suggest a contradiction with current social demand and regional policies.

Keywords

Land use history; Landscape heterogeneity; Temporal variation in ecosystem service bundles; Landscape multifunctionality; Scale of multifunctionality; Central French Alps; Stubai

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Introduction

Mountains of the world have been particularly dynamic regions through history in terms of land use and associated environmental and biodiversity change (Körner and Spehn 2002). They are expected to experience rapid and sometimes abrupt changes in response to the combination of climate, political and socio-economic change (Körner et al. 2005). Agriculture was allowed by forest clearing in temperate mountain regions, and through centuries local demography, regional economy and later larger-scale social and economic dynamics have driven land use changes (Jepsen et al. 2015; Mottet et al. 2006; Schneeberger et al. 2007). Specifically, in European mountains rural population and highest land use intensity for subsistence agriculture peaked in the middle of the nineteenth century. The transition to a partial market economy with export to regional markets was followed after World War II by a radical transformation due to emigration to cities and mechanisation (Flury et al. 2013). This transformation has taken various shapes across regions: some have experienced widespread land abandonment, whereas others still retain lively agriculture (Hinojosa et al. 2016b; Tappeiner and Bayfield 2004; Vacquie et al. 2015; Zimmermann et al. 2010).

Such land use changes and their expression in terms of landscape change have been associated with changes in demand and supply of ecosystem services (ES). Indeed, mountain landscapes are key providers of ES—particularly water regulation, timber production, grazing, recreation and numerous cultural values—which make substantial contributions to lowland and highland economies (Grêt-Regamey et al. 2012; Körner et al. 2005). The global-scale synthesis of 51 cases of ES changes in mountains revealed that similar changes in land use intensity are associated with repeatable temporal changes in the bundles of ES supplied by mountain landscapes (Locatelli et al. 2017). Typically, in European mountain regions, such as Switzerland (Briner et al. 2013; Bürgi et al. 2015; Hirschi et al. 2013), Austria (Schirpke et al. 2013a) or Italy (Egarter Vigl et al. 2016), agricultural provisioning services have decreased since the nineteenth century; meanwhile, regulating services such as carbon, water quality, water flow regulation or slope stabilisation have increased, and cultural services show no clear trend. Drivers were generally environmental policies reflecting increasing demand for regulating services, and less demand for food because of agricultural and trade policies, or the higher competitiveness of other regions worldwide. In some other European upland regions where agriculture has been abandoned and land converted to nature conservation, the decrease in provisioning ES has been mostly to the benefit of heritage value and recreation services for outside beneficiaries (Haines-Young et al. 2012; Morán-Ordóñez et al. 2013).

Overall, these temporal variations in ES bundles reveal broad land use/land cover trends, especially shifts in forest cover (Locatelli et al. 2017). However, for specific regions and landscapes, detailed historical trajectories of ES supply are shaped by the interplay of land use intensity and landscape structure, social values and interactions with landscapes, as well as land use legacies (Bürgi et al. 2015; Plieninger et al. 2015; Tomscha and Gergel 2016). Specifically, ES supply is shaped at field level by past and present land use intensity and legacies on vegetation and soils (Quétier et al. 2007). Second, landscape spatial patterns influence landscape-scale ES supply through grain size (the extent of homogenous land cover units) and connectivity (Grêt-Regamey et al. 2014; Mitchell et al. 2015; Syrbe and Walz 2012; Verhagen et al. 2016). Therefore, analyses of historical trajectories of ES need to consider the combined effects of changes in land use intensity and in landscape pattern.

To date, there is very limited empirical evidence for historical trajectories of multiple ES and their relationships with trajectories of land use (Egarter Vigl et al. 2016, 2017; Jiang et al. 2013; Lautenbach et al. 2011; Locatelli et al. 2017; Renard et al. 2015). To our knowledge, their relationships with landscape spatial pattern have never been explored. In this study, we aimed to quantify synchronous variations in land use spatial patterns and ES supply by mountain landscapes dominated by grasslands. First, we hypothesised that through history the greatest landscape heterogeneity would be associated with the greatest diversity in ES, also referred to as ‘multifunctionality’. From first principles, greater diversity in land cover is expected to lead to greater diversity in ES due to contrasts in ES values across land use/ cover types of varying intensity. Second, we hypothesised that through the recent history of agricultural extensification, with possible intensification over more favourable areas, field/ patch-scale ES diversity decreased while landscape-scale diversity ES diversity increased. This would result from two mechanisms: first the change in landscape grain, where more intensively used areas become spatially aggregated over history, whereas less productive areas such as steep upper slopes are extensified or abandoned; and second the shift from traditional, intermediate management intensity producing multiple ES at field scale, to either low or high intensities, each of which are associated with fewer ES (Locatelli et al. 2017).

To address such hypotheses, a quantitative approach for quantifying ES diversity at landscape scale is required. Here, we developed a novel approach based on diversity metrics to quantifying ES diversity at landscape scale, which we applied to analyse the joint dynamics of land use and ES in two case studies from the Central French Alps and Austrian Tirol. Since the nineteenth century, agriculture has gradually declined in the two landscapes (Quétier et al. 2007; Tappeiner et al. 2008), with a gradual shift from traditional subsistence farming based on livestock production, to more extensive systems where traditional practices coexist with both more intensive production (Stubai, valley bottom) and decreased management intensity (both sites), and possibly abandonment and reforestation (Stubai, steeper high altitude slopes) (Tasser et al. 2007). Along with a general social trend of decreasing mountain rural population and farm numbers, these trends have been allowed by external income from subsidies for mountain farming and agri-environmental management, and from tourism.

For each site, we linked documented land use history since the nineteenth century with modelled ES supply capacity based on vegetation taxonomic or functional composition and soil properties (Lavorel et al. 2011; Schirpke et al. 2013a). Similar to Lautenbach et al. (2011), we focused on place-based ES capacity, defined by Bürgi et al. (2015) as those ES that are available at a specific place during a certain period as a result of its environmental, land use, socio-economic, cultural, technological and governance context. As a result, and in contrast with Jiang et al. (2013) or Renard et al. (2015), we did not evaluate realised ES flow sensu Bürgi et al. (2015). Patterns for each of the two sites are presented and discussed in the context of their respective land use histories and considering implications for spatially explicit landscape-scale management of ecosystem services.

Methods

Study sites

Patterns of joint spatial variation in land use and ecosystem services were analysed at two mountain grassland sites for which extensive knowledge and field data were available regarding land use history since the nineteenth century, ecological processes underpinning the provisioning of ecosystem services and actual ecosystem service provision. The two sites illustrate alternative historical trajectories of agricultural development in the Alps (Tappeiner et al. 2003), with the persistence of livestock production as a common central feature. Today, agri-environmental policies promote sustainable management and biodiversity conservation, with for instance measures supporting mowing and extensive grazing (Schermer et al. 2016), and the continuation of management in areas threatened by abandonment (Benton 2012; Jepsen et al. 2015).

The Lautaret site within the Central French Alps long-term socio-ecological research (LTSER) (Lavorel et al. 2012) is located on the south facing slopes of the Romanche valley above the village of Villar d’Arène (45.03° N, 6.24° E) (Fig. 1). The area ranging between 1552 and 2442 m a.s.l. covers 13 km^2 and is composed nearly solely of grasslands (with the exception of the village and hamlets, and of riparian trees). The lower part of the site (1552–ca. 2000 m) was used from the fifteenth century for cropping on terraces, whereas mowing was originally located above this cropping belt and until a maximum altitude of 2400 m, the upper slopes being dedicated to summer grazing (Girel et al. 2010). Lautaret illustrates a dynamics representative of higher altitude areas in the southern French Alps, where, although the generic socio-economic and demographic trends for European mountains apply, livestock rearing has been maintained and abandonment is rare (Hinojosa et al. 2016b). In-depth analysis of farmers’ motivations in the region showed a strong place attachment in high vs. lower mountain farmers, overriding effects of marginal farm economic profit (Hinojosa et al. 2016a). This motivation has enhanced the development of complementary activities to farming, especially in the tourism sector, and thus supported household income and farm persistence.

The Stubai site is part of the LTSER platform ‘Tyrolean Alps’ located in the Central Alps (Tyrol, Austria) 30 km south of Innsbruck (46.55–47.15 N–11.6–11.25 E) (Tappeiner et al. 2013). It ranges from 900 to 2600 m a.s.l. and covers approx. 80 km^2. A long tradition of farming systems has led to a diversity of grassland types, ranging from fertilised meadows in the valley bottom (referred to as ‘grassland mown’), which are cut several times per year, to lightly used grassland above 1500 m a.s.l., which is cut one to two times per year or used as pastures (referred to as ‘grassland mown/grazed’) (Fig. 1). Whereas in the middle of the nineteenth century ~ 70% of the population of Tyrol was working in forestry and agriculture, a fast decrease was recorded since 1950 resulting in less than 5% employees in the primary sector today. Today, 80% farmers are working part time and the viability of extensive farming systems at higher altitudes is strongly linked to subsidies, pluri-activity income (e.g. off-farm by tourism), demand for local products, etc. (Schermer et al. 2016). A glacier offers almost year-round skiing, and together with a high scenic beauty, the valley is an attractive tourist destination (Schirpke et al. 2013b).

The two sites were previously surveyed exhaustively for parcel-scale soil characteristics, plant composition, plant functional traits and indicators of ecosystem functioning and ecosystem services using plots distributed across grassland types. See Lavorel et al. (2011) and Schirpke et al. (2017) as well as Tappeiner et al. (2008) for a detailed description of the site and of field measurements at Lautaret and Stubai respectively.

Historical grassland landscape change

Historical land use and associated patterns of landscape change were described at each site using time series of land use maps. Appendix 1 details grassland use classifications and presents historical maps for the two sites.

At Lautaret, we analysed orthophotos from 1952, 1961, 1971, 1986, 2001 and 2009 where cropping and mowing were identified by visual analysis; land use registers from 1810, 1971 and 1974 where cropped, mown and grazed areas were mapped (Girel et al. 2010); and interviews with local farmers (1996, 2003, 2009) to build a spatially explicit database of past and present land use (see Girel et al. 2010; Lamarque 2012 for details). All data were consolidated using cadastre maps and referenced in a Geographic Information System at 30 m resolution, including also a 10-m Digital Elevation Model under ArcGiS 9.2, ESRI. This data allowed us to determine at each date the area under cropping on terraces, the area under mowing and the rest of grasslands being grazed (with the exception of a few small areas that are still grassy but neither mown nor grazed). The combination of all three sources of information, plus the examination of old postcards, enabled cross-checking the extent of hay meadows in particular. Spatial data on grassland fertilisation was only available for 2001 and 2009, but based on historical and interview information, we assumed that until the 1970s all terraced hay meadows were fertilised; based on a statistical model of the current distribution of fertilisation, we then reduced the fertilised area linearly through time according to slope and accessibility. This formed the basis for the identification of six grassland types based on historical and land use as well as management practices at a given date (Quétier et al. 2007) (Fig. S1). These comprised three types on previously cultivated terraces (T1: mown and fertilised, T2: mown, T3: grazed in spring and autumn by sheep and cattle), and three on never cultivated grassland (T4: mown, T5: previously mown and currently grazed in summer by sheep and cattle, T6: never mown and grazed in summer by sheep and cattle since the Middle Ages, above 2000 m) (Lavorel et al. 2011). Figure S1 shows the graphical representation of land use dynamics at Lautaret, and Fig. S2 shows maps of grassland types for selected time steps.

In Stubai, historical land use/cover was mapped on the basis of historical maps and orthophotos for 1861, 1954, 1973, 1988 and 2013. The maps were integrated with data from agricultural censuses and village chronicles and reviewed by farmers to ensure their accuracy. The Francisco–Josephinian Cartographical Register (third cartographical register of the Austrian crownlands; 1:25,000) from 1861 marks the start of spatially explicit historical land use/cover. Herein, different land use/cover types (i.e. forest, meadows, pastures, larch meadows, permanent crops, arable land, settlements) as well as specific landscape features (i.e. rivers, moors, rocks) were mapped (Tasser et al. 2009). The maximum known grassland extent in 1861 was used as a baseline for the analysis (Egarter Vigl et al. 2016). As for Lautaret, grassland types were classified based on historical land use changes, but in contrast to Lautaret which encompasses homogenous geology and aspect, the definition of grassland types with similar environmental and management characteristics (i.e. plant communities) integrated geology, altitude, aspect and slope in addition to management category (fertilised, unfertilized, abandoned) so as to provide reliable data for trait-based ES modelling (Table S1). Grassland patches smaller than 20 ha were excluded from further analysis which resulted in 18 grassland types in 1861, 32 in 1954, 30 in 1973, 23 in 1988, and 21 in 2013. Figure S4 shows the graphical representation of land use dynamics in the Stubai Valley, and Fig. S3 shows maps of all defined grassland types for selected time steps.

We thus obtained for each site a historical series of grassland use maps for which patterns of landscape change were described by a set of spatial pattern indices known to both reflect agricultural use systems and potential ecological impacts (Dobbs et al. 2014; Grêt-Regamey et al. 2014; Laterra et al. 2012; Syrbe and Walz 2012; Tappeiner and Tappeiner 2009). Landscape metrics were calculated at different levels with VLATE 2.0 beta within ArcGIS 10.1. At the landscape level (all grassland types), total area, number of patches, mean patch size/edge and Shannon diversity (McGarigal 2015) were used to evaluate historical changes and to document heterogeneity of grassland types at the two sites. Landscape metrics at class level (individual grassland types), including total area, number of patches and mean patch size/edge, were then calculated to provide insights into spatial characteristics for different time steps for each grassland type. The selected landscape metrics ‘Number of Patches’ and ‘Mean Patch Size’ are strong and consistent class-level components and are used at landscape level to examine spatial structure in multiclass patch mosaics (Cushman et al. 2008). Both metrics exhibit simple scaling relationships and are considered robust across different landscapes (i.e. changing extent) (Wu et al. 2002). The Shannon Diversity Index is a measure of diversity applied here to landscape. This index equals to ‘0’ when the landscape contains only one patch type (i.e. no diversity). It increases as the number of different patch types (i.e. patch richness, PR) increases and/or the proportional distribution of area among patch types becomes more equitable (McGarigal 2015). More precisely, in a landscape where the number of grassland types does not change, the Shannon Diversity Index only depends on the proportional distribution of the area among grassland types (the more equitable the higher the index value). On the other hand, in a landscape where both number of grassland types and the proportional distribution of the area among grassland types change through time, careful interpretation of the course of the index values is required and comparison between two distinct landscapes is often problematic (Li et al. 2005).

To describe topographic variations within grassland types and their constraining effects on mechanisation, we calculated average surface roughness by identifying the mean absolute differences of the elevation value of each patch from the mean value of the grassland type (Hoechstetter et al. 2008). In addition, we calculated cost distance from settlements to individual patches to include socio-economic factors. The intensity of use strongly depends on the accessibility and travel time: the probability for abandonment/lower land use intensity increases with increasing management costs. For details, please refer to Schirpke et al. (2012) and references therein.

Historical patterns in landscape level ecosystem service delivery

Grassland ecosystem service models—

We chose to use trait-based models of ecosystem services given their ability to capture variations in ES in response to detailed management rather than just broad land use classes (Lavorel et al. 2017; Lavorel et al. 2011). At each site, indicators of two provisioning (fodder quantity and quality), four regulating (climate regulation, water quality regulation by soil nitrate retention, maintenance of soil fertility and erosion regulation by the root profile) and one cultural (aesthetic value at field scale) ecosystem service considered as important by local and regional stakeholders were calculated for each grassland type and mapped for each historical date based on the corresponding land use map. Briefly, based on previous studies at the two sites, we used statistical models of each ES combining soil and plant trait parameters (Table 1). These models were established within or across the two sites based on field data for multiple plant and soil parameters and for ecosystem properties. Table 1 provides the list of supporting studies for each ES, each of which details how specific statistical models were obtained. Figures S5 and S6 present ES values for different grassland types at each site. ES values for each grassland type at each site were calculated as averages of observed values across representative parcels (typically 5–15 parcels per grassland type) and applied to all corresponding patches. Thus, these models calculated at field scale did not account for possible effects of landscape configuration, which are unlikely to be significant for any of the indicators of ecosystem service supply capacity considered. This is also distinct from assessing landscape flows of ecosystem services, where configuration of grassland patches would influence the demand for regulating services such as water quality and erosion regulation depending on the sources of nutrients and sediments due to management and topography (Mitchell et al. 2015; Verhagen et al. 2016). Also, it is important to note here that while modelled ES values for different grassland types considered past land use, we used fixed ES values per grassland type over time—as done by Lautenbach et al. (2011). In the absence of suitable data to investigate such variation, this neglects potential ecological changes, such as climate, soil erosion on cropland, changes in fertility and especially changes in practices and technology. This could be improved by incorporating historical yield data (as done by e.g. Jiang et al. 2013; Renard et al. 2015), and in-depth analysis of changes in practices, but was outside the scope of this study.

Analyses of temporal changes in ecosystem services and their spatial pattern—

We first described temporal trajectories of ES bundles at landscape level graphically using spider diagrams of total supply for each ES across the landscape, aiming to identify shifts in dominant sets of ES across history following archetypes described by Locatelli et al. (2017), and periods of greater multifunctionality—i.e. more even representation across different ES. For Lautaret, the analysis of total supply of individual ES was restricted to grassland types 1–5, thus omitting the summer pasture and steep grazed slopes, whose area has been stable over time, and which would otherwise dominate all analyses as they represent ca. 50% of the total landscape area. In Stubai, analyses were restricted to the original grassland area, considering for each date only grassland types therein (including abandoned), for which ES were calculated.

The description of landscape ES diversity has not been addressed in detail in previous literature, which only considers either ES richness (i.e. the number of distinct values per ES) or at best Simpson diversity (e.g. Crouzat et al. 2015). To provide more advanced insights into the spatial variability of ES across landscapes, we developed two new indices. First, we quantified spatial variability in the supply of individual services using the landscape area-weighted variance for individual ES. This was calculated as the sum across grassland types of the square of the difference between the ES value in this type and the overall mean of this ES across grassland types, with each grassland type weighted by its landscape area percentage at each date. The square root of this index (representing a weighted standard deviation) quantifies the expected difference in ES values between two randomly sampled landscape pixels. As such, it represents the spatial variability in values across the landscape for each ES: high spatial variability indicates strong contrasts in ES values resulting for example from combinations across the landscape of intensively and extensively managed grasslands, whereas low spatial variability is associated with more even ES values across less contrasted grassland types, typically resulting from the dominance of extensively managed grasslands.

We then examined spatial variability in the supply of multiple ES across the landscape by calculating for each date ES β-diversity, indicating the turnover in ES bundles across pixels across the landscape. Calculating diversity indices implies deciding whether an ES is present or absent from a given landscape patch. This was done for each grassland type by comparing its ES value to the median across all types, with a value below the median resulting in an absence score, and a value above the median a presence score. These presence-absence values by grassland type were then weighted by the relative proportion of the grassland type in the landscape at each time step. A Shannon diversity index was then calculated from these weighted values both within grassland types, yielding the α-diversity, and across all grassland types to give the γ-diversity. Thus, α-diversity was the diversity in ES values within an individual grassland type, and γ-diversity is diversity in ES values across all grassland types. The β diversity was then calculated as the difference between the γ-diversity and the mean α-diversity across grassland types at each time step. Temporal changes in ES β-diversity were compared graphically to changes in land cover (grassland types) β-diversity.

Results

Historical landscape change

At the Lautaret site, total grassland area first increased from nearly 80 to 100% of the landscape as a result from crop conversion from the beginning of the nineteenth century until the 1970s. Over the same period, in Stubai the area of managed grassland decreased to 30% of the initial area in 1861, with this trend stabilising in the late 1980s (Fig. 2). At both sites, landscape diversity (Shannon index) peaked from the 1950s to the 1970s and has gradually decreased since (Fig. 3). At Lautaret, this period corresponded with the coexistence of remaining cropping areas closest to the settlements with mown grasslands on terraces (T1 and 2) and a still large proportion of mowing in the never ploughed grasslands (T4). In Stubai, the highest values for landscape diversity in 1954 and 1973 reflect the high number of grassland types at these two dates, and specifically the variety of secondary successional stages on abandoned grasslands. These became forest subsequently and are no longer incorporated in the grassland area for metrics calculated at later dates.

At both sites, mown grasslands have markedly decreased in area since the nineteenth century (Fig. 2), with a concurrent decrease in the number of patches; therefore, the size of remaining mown patches has increased and their shape has become more regular (Fig. 4). In mountains, terrain is a critical determinant of land use change due to constraints on mechanisation. These trends thus reflect the period of mechanisation and decreasing available manpower, restricting mowing to the most accessible and easy-to-harvest/fertilise areas. For instance, at Lautaret, until the 1970s mowing extended over cropping in terraces of increasing terrain roughness. After this, mowing on terraces (T1–2) contracted to easily accessible parcels (smallest available cost distances within each area) and to decreasingly rough terrain to currently reach a stable distribution to flattest areas (Suppl. Mat. Fig. S7). On never ploughed grasslands (T4), the contraction of mowing since the early 1970s was driven by accessibility. Over the same periods, there was a linear decreasing relationship ($R^2 = 0.946$, $p < 0.001$) between mowing vs. grazing and cost distance for never ploughed grasslands (T4). In Stubai, today remaining grassland patches are at a lower cost distance than in the past, but the trend of abandonment continues because land use decision mechanisms have changed as agricultural income is of lesser importance to households. At both sites, mown parcels have thus been converted to pastures under extensive grazing, whose area and patch size have been increasing (Fig. 4). In Stubai, grasslands of high land use intensities have increased in the valley bottom since the 1950s due to intensification (Fig. 2). However, this represents a small area compared to the overall trend of abandonment. Natural reforestation has occurred on one third of areas abandoned since the 1950s, located in the sub-alpine (88.4%) and the alpine/nival (9.5%) belt.

Historical changes in ecosystem service bundles

These historical land use trends have been paralleled by changes in the bundles of provisioning, regulating and cultural services at both sites (Fig. 5). At both sites, the main objective of grassland management shifted from an early priority on provisioning services to multifunctionality characterised by rich bundles of regulating and cultural services coexisting with a somewhat decreased fodder production since the 1970s.

Specifically, at Lautaret the early period of crop conversion to mowing on terraces resulted in an increase in fodder quantity and quality due to increasing grassland area, along with an increase in water quality and climate regulation until the 1970s (Fig. 5a). Since this period, with the conversion of mowing to grazing, provisioning services and these two regulating services have remained stable at landscape scale, but have been accompanied by a decrease in erosion control and in grassland aesthetic value (Fig. 5b). Overall, these trends depict an increase in multifunctionality until the 1970s, and a decrease since, as a result of landscape simplification towards a stronger prevalence of grazing.

At the Stubai site, grassland abandonment started as early as the end of the nineteenth century. This resulted until the 1970s in a steady decrease in provisioning services due to decreasing grassland area, and increasing erosion control and climate regulation associated with shrubs (e.g. *Rhododendron*) on abandoned grasslands (Fig. 5c). These trends have continued since then, especially the marked increase in water quality explained by better filtering capacity of extensively used/abandoned sites (Fig. 5d), while grassland aesthetic value has remained stable. So overall, there was no clear signal of changing multifunctionality in the Stubai landscape, but a shift from provisioning to regulating services.

Historical trajectories of spatial variability of ecosystem service supply

At both sites, spatial variability of individual ES (e.g. fodder production and quality, water quality and climate regulation), quantified by their landscape weighted variance, increased over time, with the fastest increase between the 1950s and the 1970s (Figs. 6 and 7). This common pattern was however linked to distinct land use dynamics. At both sites, the initial increase until the 1970s paralleled the increase in grassland use diversity (Shannon index). This diversification of grassland types resulted from crop conversion to mown grasslands at Lautaret, but from the onset of grassland abandonment in Stubai. Subsequent dynamics of continued increasing (provisioning services) or stabilising (regulating services and aesthetic value) spatial variability of ES also reflected different land use trends across sites. At Lautaret, conversion from mowing to grazing which contrast in fodder quantity vs. quality has gradually increased spatial variability for provisioning services. This increased dominance of grazed areas also explains the slightly decreasing spatial variability for erosion control and aesthetic value (Fig. 6). In Stubai, recent intensification in the valley bottom has increased fodder quantity but decreased regulating services; this contrasts with increasing regulating services in abandoned alpine grasslands, especially water quality and carbon storage (Fig. 7).

The two sites illustrated different historical trajectories in landscape scale turnover in multiple ES (β-diversity) (Fig. 8). At Lautaret, ES spatial variability has been increasing through history, reflecting increased contrasts across the landscape in ES bundles (Fig. 8a). In Stubai, the initial increase in ES spatial variability until 1954 was followed by a marked decrease, especially between 1973 and 1988 (with a slight rebound to the present) (Fig. 8b). The patterns for each of the two sites essentially parallel respective patterns in grassland landscape-scale ES diversity (γ-diversity), while mean patch-scale ES diversity (α-diversity; i.e. patch-scale multifunctionality) showed similar slightly humped-back trajectories at the two sites, with a maximum from the 1950s to the 1970s. At Lautaret, landscape-scale ES diversity (γ-diversity) reflects patterns of spatial variability for individual ES (Fig. 6), and is dominated by the increasing contrast across the landscape over time between contracting more intensively managed mown grasslands, associated with moderate fodder quantity, higher fodder quality and higher aesthetic value on the one hand, and expanding extensively managed pastures with higher fodder quantity but poorer quality, lower aesthetic value and higher regulating services (except erosion control). In Stubai, the decrease in mean patch-scale ES diversity (α-diversity) after 1973 is mainly a consequence of the increasing abandonment of grassland above 1500 m a.s.l., as abandoned grasslands provide low levels for most ES. Together, abandonment and the intensification of the meadows in the valley bottom result in fewer grassland types, larger patches and overall a coarser grained land use pattern, increasing ES trade-offs across the whole landscape (increasing ES β-diversity).

Discussion

The exploration of long-term dynamics of ecosystem services in relation to land use and landscape history is a critical area of research, with implications for developing sustainable future landscapes (Plieninger et al. 2015). Very few studies have analysed temporal changes in ecosystem services bundles (aEgarter Vigl et al. 2016, 2017; Jiang et al. 2013; Lautenbach et al. 2011; Locatelli et al. 2017; Renard et al. 2015), especially in mountain regions (Egarter Vigl et al. 2017; Locatelli et al. 2017). To our knowledge, ours is the first study exploring the spatial patterns associated with these trajectories. To explore joint temporal trajectories of spatial patterns in land use and in ES bundles, we used historical time series for land use and modelled ecosystem services, and developed novel analyses of spatial diversity in ES supply capacity at different scales, from the patch to the landscape. Just as mapping of current ES is subject to uncertainties in land use data (Vannier et al. 2017), historical studies are contingent on uncertainties in past land use mapping. Nevertheless, we believe that the contrasts in ES bundles and their spatial distribution through time illustrated here for two alpine sites can be considered as robust. Below, after briefly summarising historical changes in land use spatial patterns and the provision of multiple ES, we successively discuss their implications for spatial variability in individual ES and in ES bundles, with special interest in their scales of variation. We end by reflecting on the implications of such results for landscape management and policies.

Although the two sites have contrasting histories and levels of grassland use complexity, both showed maximum spatial variability in grassland types in the 1950s to the 1970s. This reflected land cover fragmentation (more numerous, smaller patches of less regular shape and of different types) due to land use diversification allowed by increased mechanisation, fertilisation and emigration to cities (Jepsen et al. 2015; Siegl and Schermer 2010). Since the 1950s, market globalisation, emigration and part-time farming allowed by employment outside the agricultural sector, and recent specialisation of products, have resulted in economic, technical and labour motivations for enlarging remaining farms and managed patches, and in the case of Stubai for increasing fertilisation in the valley. As a result, landscape heterogeneity has decreased, with fewer types of larger and more contrasted patches. This is consistent with other rural regions in Europe, especially mountains (Egarter Vigl et al. 2016; MacDonald et al. 2000; Mottet et al. 2006), and reflects land management trends during recent European history (Levers et al. 2016).

These historical changes in grassland use from a local, labourintensive, subsistence agriculture, to labour-limited livestock production influenced by market globalisation and by (urban) social preferences and ES demands, directly impacted the provision of multiple ES. Across different regions of the Alps, Egarter Vigl et al. (2016) found three different historical trajectories of ES bundles: (i) from specialisation in provisioning ES to multifunctionality, (ii) overall reduction of ES capacities and (iii) stable ES bundles. Our analyses showed how detailed land use histories are reflected in such changes in landscape-scale bundles of ecosystem services across sites. At Lautaret, our hypothesis that greater spatial diversity in land use would translate to greatest multifunctionality at landscape level (Fig. 6) (landscape multifunctionality, sensu Mastrangelo et al. 2014) was confirmed: the 1950s–1970s period of greatest land use spatial diversity (Fig. 3a, Shannon index) also corresponded with the period of greatest patch-level multifunctionality of simultaneous supply of provisioning, regulating and cultural services (Fig. 8a, α-diversity) (joint ES supply, sensu Mastrangelo et al. 2014). Since then, grassland type diversity (Shannon index) has been decreasing, and so has patch-level multifunctionality, with an overall shift towards less cultural ES and more regulating ES (except erosion). The Stubai valley illustrates a different dynamics where greatest grassland landscape-level multifunctionality occurred at the beginning of the nineteenth century (Fig. 7), whereas spatial variability of grassland types peaked during the 1950s–1970s after the onset of abandonment (Fig. 3b, Shannon index). Both landscape-level multifunctionality and spatial variability of grassland types have decreased since, as a result of the contraction of the grassland area after abandonment of higher slopes. The recent and future expected trends towards minimal mowing at Lautaret and abandonment at the Stubai site will further increase the share of regulating services (climate regulation through soil carbon stocks; water quality regulation through nutrient retention; erosion control), at the expense of cultural services (plant diversity, aesthetic value, landscape scenic beauty) (Schirpke et al. 2013b, Lamarque et al. 2014), and of regulation of vole outbreaks at Lautaret (Halliez et al. 2015). These trends in ES bundles suggest a contradiction with current demand for cultural services and for the maintenance of mountain production and its social values, which underpin niche-marketing and subsidies for mountain agriculture, but do not target regulating services (Schermer et al. 2016).

The area-weighted variance in ES showed how increasing spatial variability in grassland use until the 1970s was paralleled by increasing spatial variability for individual ES at both sites. This spatial variability in individual ES continued to increase subsequently in spite of landscape simplification, reflecting increasing contrasts across the landscape between grassland types' supply capacities. This suggests different scales in landscape-level variability for individual ES, shifting from being small-grained in the earlier period, to being coarse-grained in the later period. For provisioning services, this is a direct reflection of the changing practices and associated land tenure arrangements, and how they affect place-based ES capacity (sensu Bürgi et al. 2015). For example, at Lautaret the collective management of parcel allocation for mowing enabled the consolidation of mown areas for mechanised harvest by individual farmers, resulting in greater spatial aggregation for fodder quantity or aesthetic value. For regulating services such as erosion control or water quality regulation, this consolidation may ultimately reduce ecosystem service flows, as a finer-grained land use mosaic better reduces lateral flows from patch types with lower levels for these ES (e.g. intensively managed meadows). We expect that more advanced landscape-scale models accounting for lateral flows—in addition to patch-scale effects of plant composition as modelled here—would better capture such effects (Grêt-Regamey et al. 2014; Verhagen et al. 2016).

Further, our novel analysis of landscape-scale turnover of multiple ES (β-diversity) highlighted that spatial patterns for individual ES scale differently to spatial variability for multiple ES depending on the nature of grassland-use variability. At Lautaret, we observed a shift since the 1950s–1970s from landscape-level multifunctionality underpinned by patch-level multifunctionality (joint ES supply) to recent spatial segregation of ES supply across the landscape, producing a dual landscape in terms of ES. While depicting a situation of land use extensification, and although individual patches still remain relatively multifunctional, this pattern is in line with other rural regions where land use intensification and specialisation have segregated ecosystem bundles over history (Jiang et al. 2013; Renard et al. 2015). In Stubai, the decrease in total spatial diversity of multiple ES (γ-diversity) and spatial turnover (β-diversity) since the 1970s represents a more extreme version of this situation. The grassland landscape has now become dominated by abandonment, so that both patch-level (α) and landscape-level (γ) ES diversity have decreased. This diversity of combinations between grassland use spatial heterogeneity and ES diversity is congruent with the conclusion that landscape-scale multifunctionality can be obtained from either patch-level multifunctionality within moderately homogenous landscapes or from more heterogeneous landscapes (Mastrangelo et al. 2014), especially in mountain regions (Crouzat et al. 2015). Managers aiming to steer the supply of multiple ecosystem services should therefore consider the combinations of constraints to land use and practices (technical and labour constraints, land tenure, social values) along with fundamental ES capacities of different land use types (sensu Bürgi et al. 2015) and landscape biophysical processes (e.g. lateral flows of water and nutrients). In addition, our analysis did not include historical changes in management techniques (e.g. from manual to mechanised mowing, changes in fertilisation practices) or in climate, which undoubtedly influence ES supply capacity through plant species composition and soils. The detailed examination of such effects would also offer further guidance on ecological intensification of practices for the supply of multiple ecosystem services by mountain grasslands (Loucougaray et al. 2015).

With increasing concerns for sustainability and awareness of ecosystem services, the composition and configuration of landscape elements and land use pattern have become core to landscape planning (Benton 2012; Mastrangelo et al. 2014). With the recognition that landscape spatial heterogeneity (ideally in combination with extensive management) best supports dispersal of species and regulating abiotic processes, heterogeneous landscapes are favoured for sustainable landscape planning (Arponen et al. 2013; Tscharntke et al. 2005). However, the benefits of heterogeneous landscapes might differ between ecosystem services (Grêt-Regamey et al. 2014; Mitchell et al. 2015; Verhagen et al. 2016): pollination or aesthetic values for example depend on heterogeneous and connected landscapes (Benton 2012; Schirpke et al. 2013b), whereas for other ecosystem services (e.g. carbon storage) fragmentation might have no influence (Grêt-Regamey et al. 2014; Mitchell et al. 2015; Verhagen et al. 2016). Within our study, we recorded at both sites an increase in ES spatial variability through history despite grassland landscape simplification, reflecting contrasts between patches that have high values for provisioning services (e.g. fodder quantity) and patches with high values for regulating services (e.g. water quality regulation). Care is therefore warranted in associating demand for ES multifunctionality with demand for landscape heterogeneity, and desired scales of multifunctionality need to be considered (Mastrangelo et al. 2014). In addition, the present analysis deliberately focused on the high-nature value grassland component of two mountain landscapes, whereas in regions such as Stubai forest dynamics is also critical (Tasser et al. 2007). A multiscale analysis, combining the present study with a broader analysis across the entire landscape, would be required to reveal complex trade-offs and possible synergies between the management of ES multifunctionality in grasslands and whole-landscape multifunctionality.

Conclusion

To our knowledge, the relationships between historical trajectories of ecosystem service bundles and landscape spatial pattern have never been explored. Using novel diversity metrics to quantify ES diversity from patch to landscape scale, we showed for two mountain landscapes how over history changes in grassland use in response to socio-economic drivers have translated into changes in the degree and scale of landscape-scale multifunctionality. Our two case studies illustrated how not only landscape heterogeneity but also the nature of land use change influence the scaling from changes in spatial pattern for individual ES to changes for ES bundles. Thus, our hypothesis that landscape heterogeneity and ES multifunctionality should be maximised simultaneously was verified for Lautaret where management extensification has been prevalent, but not in Stubai where extensification, abandonment and intensification coexist.

At both sites, current trends towards spatial segregation of ES supply across the landscape are expected to continue in the future. Typical of many European mountain livestock production regions, future land use and ES bundles strongly rely on agricultural subsidies for managing marginal grasslands (Schermer et al. 2016), and to some extent on local markets. These economies also strongly rely on tourism for pluri-activity. Continued decrease in subsidies might complete the process of abandonment or cessation of mowing on steeper grasslands, while management will concentrate in valley bottoms. Such developments will result in more homogeneous, coarse-grained landscapes. Under the current socio-economic context, the aim of sustaining or re-establishing fine-grained landscapes is often not feasible as financial support is missing, or is not economically viable. Future landscape planning and policies might therefore focus on managing landscape and regional-scale multifunctionality: as in the past, landscape-scale multifunctionality can be at patch level within moderately homogenous landscapes, but it can also be provided by more heterogeneous landscapes. Also, the trends in ES bundles highlighted by our analyses, with decreasing cultural ES and increasing regulating ES, suggest a contradiction with social demand for cultural ecosystem services and for the support of mountain agriculture.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References

Arponen A, Heikkinen RK, Paloniemi R, Pöyry J, Similä J, Kuussaari M. Improving conservation planning for semi-natural grasslands: integrating connectivity into agri-environment schemes. Biol Conserv. 2013; 160:234–241. DOI: 10.1016/j.biocon.2013.01.018

Benton T. Managing agricultural landscapes for production of multiple services: the policy challenge. Polit Agric Int. 2012; 1:7–17.

Briner S, Elkin C, Huber R. Evaluating the relative impact of climate and economic changes on forest and agricultural ecosystem services in mountain regions. J Environ Manag. 2013; 129:414–422. DOI: 10.1016/j.jenvman.2013.07.018

Bürgi M, Silbernagel J, Wu J, Kienast F. Linking ecosystem services with landscape history. Landsc Ecol. 2015; 30:11–20. DOI: 10.1007/s10980-014-0102-3

Crouzat E, Mouchet M, Turkelboom F, Byczek C, Meersmans J, Berger F, Verkerk PJ, Lavorel S. Assessing bundles of ecosystem services from regional to landscape scale: insights from the French Alps. J Appl Ecol. 2015; 52:1145–1155. DOI: 10.1111/1365-2664.12502

Cushman SA, McGarigal K, Neel MC. Parsimony in landscape metrics: strength, universality, and consistency. Ecol Indic. 2008; 8:691–703. DOI: 10.1016/j.ecolind.2007.12.002

Dobbs C, Kendal D, Nitschke CR. Multiple ecosystem services and disservices of the urban forest establishing their connections with landscape structure and sociodemographics. Ecol Indic. 2014; 43:44–55. DOI: 10.1016/j.ecolind.2014.02.007

Egarter Vigl L, Schirpke U, Tasser E, Tappeiner U. Linking longterm landscape dynamics to the multiple interactions among ecosystem services in the European Alps. Landscape Ecol. 2016; 31:1903–1918. DOI: 10.1007/s10980-016-0389-3

Egarter Vigl L, Tasser E, Schirpke U, Tappeiner U. Using land use/land cover trajectories to uncover ecosystem service patterns across the Alps. Reg Environ Chang. 2017; doi: 10.1007/s10113-017-1132-6

Flury, C, Huber, R, Tasser, E. Future of mountain agriculture in the alpsThe future of mountain agriculture. Mann, S, editor. Springer; Berlin: 2013. 105–126.

Girel, J, Quetier, F, Bignon, A, Aubert, S. Histoire de l'Agriculture en OisansLes Cahiers Illustrés du Lautaret. Vol. 1. Station Alpine Joseph Fourier; Grenoble: 2010.

Grêt-Regamey A, Brunner SH, Kienast F. Mountain ecosystem services: who cares? Mt Res Dev. 2012; 32:S23–S34. DOI: 10.1659/MRD-JOURNAL-D-10-00115.S1

Grêt-Regamey A, Rabe S-E, Crespo R, Lautenbach S, Ryffel A, Schlup B. On the importance of non-linear relationships between landscape patterns and the sustainable provision of ecosystem services. Landsc Ecol. 2014; 29:201–212. DOI: 10.1007/s10980-013-9957-y

Grigulis K, Lavorel S, Krainer U, Legay N, Baxendale C, Dumont M, Kastl E, Arnoldi C, Bardgett R, Poly F, Pommier T, et al. Combined influence of plant and microbial functional traits on ecosystem processes in mountain grasslands. J Ecol. 2013; 101:47–57. DOI: 10.1111/1365-2745.12014

Haines-Young R, Potschin M, Kienast F. Indicators of ecosystem service potential at European scales: mapping marginal changes and trade-offs. Ecol Indic. 2012; 21:39–53. DOI: 10.1016/j.ecolind.2011.09.004

Halliez G, Renault F, Vannard E, Farny G, Lavorel S, Giraudoux P. Historical agricultural changes and the expansion of a water vole population in an Alpine valley. Agric Ecosyst Environ. 2015; 212:198–206. DOI: 10.1016/j.ecolind.2011.09.004

Hinojosa L, Lambin E, Mzoughi N, Napoleone C. Place attachment as a factor of mountain farming permanence: a survey in the French Southern Alps. Ecol Econ. 2016a; 130:308–315. DOI: 10.1016/j.ecolecon.2016.08.004

Hinojosa L, Napoleone C, Moulery M, Lambin EF. The Bmountain effect^ in the abandonment of grasslands: insights from the French Southern Alps. Agric Ecosyst Environ. 2016b; 221:115–124. DOI: 10.1016/j.agee.2016.01.032

Hirschi C, Widmer A, Briner S, Huber R. Combining policy network and model-based scenario analyses: an assessment of future ecosystem goods and services in Swiss mountain regions. Ecol Soc. 2013; 18:42.doi: 10.5751/es-05480-180242

Hoechstetter S, Walz U, Dang LH, Thinh NX. Effects of topography and surface roughness in analyses of landscape structure—a proposal to modify the existing set of landscape metrics. Landscape Online. 2008; 3:1–14. DOI: 10.3097/LO.200803

Jepsen MR, Kuemmerle T, Müller D, Erb K, Verburg PH, Haberl H, Vesterager JP, Andrič M, Antrop M, Austrheim G. Transitions in European land-management regimes between 1800 and 2010. Land Use Policy. 2015; 49:53–64. DOI: 10.1016/j.landusepol.2015.07.003

Jiang M, Bullock JM, Hooftman DAP. Mapping ecosystem service and biodiversity changes over 70 years in a rural English county. J Appl Ecol. 2013; 50:841–850. DOI: 10.1111/1365-2664.12093

Körner, C, Spehn, EM, editors. Mountain biodiversity. A global assessment. Parthenon Publishing Group; London: 2002.

Körner, C, Ohsawa, M, Spehn, E. Mountain systems. Chapter 24Millennium ecosystem assessment. Current state and trends: findings of the condition and trends working group. Vol. 1. Island press; Washington DC: 2005. 681–716.

Lamarque, P. Couplage écosystème–système socio-économique appliqué aux prairies de montagne via les services écologiques: mécanismes et dynamique. PhD thesis, Université Joseph Fourier; 2012. https://www.jardinalpindulautaret.fr/sites/sajf/files/pdf/Lamarque_Penelope_PhDThesis.pdf

Lamarque P, Lavorel S, Mouchet M, Quétier F. Plant trait-based models identify direct and indirect effects of climate change on bundles of grassland ecosystem services. Proc Natl Acad Sci. 2014; 111:13751–13756. DOI: 10.1073/pnas.1216051111 [PubMed: 25225382]

Laterra P, Orúe ME, Booman GC. Spatial complexity and ecosystem services in rural landscapes. Agric Ecosyst Environ. 2012; 154:56–67. DOI: 10.1016/j.agee.2011.05.013

Lautenbach S, Kugel C, Lausch A, Seppelt R. Analysis of historic changes in regional ecosystem service provisioning using land use data. Ecol Indic. 2011; 11:676–687. DOI: 10.1016/j.ecolind.2010.09.007

Lavorel S, Grigulis K, Lamarque P, Colace M, Garden D, Girel J, Pellet G, Douzet R. Using plant functional traits to understand the landscape-scale distribution of multiple ecosystem services. J Ecol. 2011; 99:135–147. DOI: 10.1111/j.1365-2745.2010.01753.x

Lavorel, S, Spiegelberger, T, Mauz, I, Bigot, S, Granjou, C, Dobremez, L, Nettier, B, Thuiller, W, Brun, J, Cozic, P. Coupled long-term dynamics of climate, land use, ecosystems and ecosystem services in the Central French AlpsLong term socio-ecological research: studies in society-nature interactions across spatial and temporal scales. ILTER monographs series. Singh, SJ, Haberl, H, Chertow, M, Mirtl, M, Schmid, M, editors. Springer; Dordrecht: 2012. 485–504.

Lavorel S, Bayer A, Bondeau A, Lautenbach S, Ruiz-Frau A, Schulp N, Seppelt R, Verburg P, van Teeffelen A, Vannier C. Pathways to bridge the biophysical realism gap in ecosystem services mapping approaches. Ecol Indic. 2017; 74:241–260. DOI: 10.1016/j.ecolind.2016.11.015

Levers C, Müller D, Erb K, Haberl H, Jepsen MR, Metzge MJ, Meyfroidt P, Plieninger T, Plutzar C, Stürck J. Archetypical patterns and trajectories of land systems in Europe. Reg Environ Chang. 2016; doi: 10.1007/s10113-015-0907-x

Li X, He HS, Bu R, Wen Q, Chang Y, Hu Y, Li Y. The adequacy of different landscape metrics for various landscape patterns. Pattern Recogn. 2005; 38:2626–2638. DOI: 10.1016/j.patcog.2005.05.009

Locatelli B, Lavorel S, Sloan S, Tappeiner U, Geneletti D. Characteristic trajectories of ecosystem services in mountains. Front Ecol Environ. 2017; 15:150–159. DOI: 10.1002/fee.1470

Loucougaray G, Dobremez L, Gos P, Pauthenet Y, Nettier B, Lavorel S. Assessing the effects of grassland management on forage production and environmental quality to identify paths to ecological intensification in mountain grasslands. Environ Manag. 2015; 56:1039–1052. DOI: 10.1007/s00267-015-0550-9

MacDonald D, Crabtree JR, Wiesinger G, Dax T, Stamou N, Fleury P, Gutierrez Lazpita J, Gibon A. Agricultural abandonment in mountain areas of Europe: environmental consequences and policy response. J Environ Manag. 2000; 59:47–69. DOI: 10.1006/jema.1999.0335

Mastrangelo ME, Weyland F, Villarino SH, Barral MP, Nahuelhual L, Laterra P. Concepts and methods for landscape multifunctionality and a unifying framework based on ecosystem services. Landsc Ecol. 2014; 29:345–358. DOI: 10.1007/s10980-013-9959-9

McGarigal, K. FRAGSTATS help. 2015. Available at the following web site: https://www.umassedu/landeco/research/fragstats/documents/fragstatshelp42pdf

Mitchell MG, Suarez-Castro AF, Martinez-Harms M, Maron M, McAlpine C, Gaston KJ, Johansen K, Rhodes JR. Reframing landscape fragmentation's effects on ecosystem services. Trends Ecol Evol. 2015; 30:190–198. DOI: 10.1016/j.tree.2015.01.011 [PubMed: 25716547]

Morán-Ordóñez A, Bugter R, Suárez-Seoane S, de Luis E, Calvo L. Temporal changes in socio-ecological systems and their impact on ecosystem services at different governance scales: a case study of heathlands. Ecosystems. 2013; 16:765–782. DOI: 10.1007/s10021-013-9649-0

Mottet A, Ladet S, Coque N, Gibon A. Agricultural land-use change and its drivers in mountain landscapes: a case study in the Pyrenees. Agric Ecosyst Environ. 2006; 114:296–310. DOI: 10.1016/j.agee.2005.11.017

Plieninger T, Kizos T, Bieling C, Dû-Blayo L, Budniok M, Bürgi M, Crumley C, Girod G, Howard P, Kolen J. Exploring ecosystem-change and society through a landscape lens: recent progress in European landscape research. Ecol Soc. 2015; 20(2):5–10. DOI: 10.5751/ES-07443-200205

Quétier F, Thébault A, Lavorel S. Plant traits in a state and transition framework as markers of ecosystem response to land-use change. Ecol Monogr. 2007; 77:33–52. DOI: 10.1890/06-0054

Renard D, Rhemtulla JM, Bennett EM. Historical dynamics in ecosystem service bundles. Proc Natl Acad Sci. 2015; 112:13411–13416. DOI: 10.1073/pnas.1502565112 [PubMed: 26460005]

Schermer M, Darnhofer I, Daugstad K, Gabillet M, Lavorel S, Steinbacher M. Institutional impacts on the resilience of mountain grasslands: an analysis based on three European case studies. Land Use Policy. 2016; 52:382–391. DOI: 10.1016/j.landusepol.2015.12.009

Schirpke U, Leitinger G, Tappeiner U, Tasser E. SPA-LUCC: developing land-use/cover scenarios in mountain landscapes. Ecol Inform. 2012; 12:68–76. DOI: 10.1016/j.ecoinf.2012.09.002

Schirpke U, Leitinger G, Tasser E, Schermer M, Steinbacher M, Tappeiner U. Multiple ecosystem services of a changing Alpine landscape: past, present and future. Int J Biodivers Sci Ecosyst Serv Manag. 2013a; 9:123–135. DOI: 10.1080/21513732.2012.751936

Schirpke U, Tasser E, Tappeiner U. Predicting scenic beauty of mountain regions. Landscape Urban Plan. 2013b; 111:1–12. DOI: 10.1016/j.landurbplan.2012.11.010

Schirpke U, Kohler M, Leitinger G, Fontana V, Tasser E, Tappeiner U. Future impacts of changing land-use and climate on ecosystem services of mountain grassland and their resilience. Ecosyst Serv. 2017; 26:79–94. DOI: 10.1016/j.ecoser.2017.06.008 [PubMed: 31110934]

Schneeberger N, Burgi M, Hersperger AM, Ewald KC. Driving forces and rates of landscape change as a promising combination for landscape change research—an application on the northern fringe of the Swiss Alps. Land Use Policy. 2007; 24:349–361. DOI: 10.1016/j.landusepol.2006.04.003

Siegl, G, Schermer, M. Kulturlandschaft woher?Wir Landschaftsmacher. Vom Sein und Werden der Kulturlandschaft in Nord-, Ost- und Südtirol. Tasser, E, Schermer, M, Siegl, G, Tappeiner, U, editors. Athesia; Bozen: 2010. 57–102.

Syrbe R-U, Walz U. Spatial indicators for the assessment of ecosystem services: providing, benefiting and connecting areas and landscape metrics. Ecol Indic. 2012; 21:80–88. DOI: 10.1016/j.ecolind.2012.02.013

Tappeiner, U, Bayfield, N. Management of mountainous areasEncyclopedia of life support systems (EOLSS), vol land cover and land use-land use management. Developed under the Auspices of the UNESCO. Verheye, W, editor. EOLSS Publishers; Oxford: 2004.

Tappeiner, U; Tappeiner, G. On the ability of landscape metrics to capture substantial landscape changes—a case study. In: Breuste, J; Kozová, M; Finka, M, editors. European landscapes in transformation: challenges for landscape ecology and management. European IALE conference 2009, Salzburg; Bratislava: Slovak University of Technology; 2009. 340–350.

Tappeiner, U, Tappeiner, G, Hilbert, A, Mattanovich, E, editors. The EU agricultural policy and the environment, evaluation of the Alpine region. Blackwell; Berlin: 2003.

Tappeiner U, Tasser E, Leitinger G, Cernusca A, Tappeiner G. Effects of historical and likely future scenarios of land use on above- and belowground vegetation carbon stocks of an Alpine Valley. Ecosystems. 2008; 11:1383–1400. DOI: 10.1007/s10021-008-9195-3

Tappeiner, U, Borsdorf, A, Bahn, M. Long-term socio-ecological research in mountain regions: perspectives from the Tyrolean AlpsLong term socio-ecological research. Singh, SJ, Haberl, H, Chertow, M, Mirtl, M, Schmid, M, editors. Springer; Dordrecht: 2013. 505–525.

Tasser E, Tappeiner U. New model to predict rooting in diverse plant community compositions. Ecol Model. 2005; 185:195–211. DOI: 10.1016/j.ecolmodel.2004.11.024

Tasser E, Walde J, Tappeiner U, Teutsch A, Noggler W. Land-use changes and natural reforestation in the Eastern Central Alps. Agric Ecosyst Environ. 2007; 118:115–129. DOI: 10.1016/j.agee.2006.05.004

Tasser E, Ruffini FV, Tappeiner U. An integrative approach for analysing landscape dynamics in diverse cultivated and natural mountain areas. Landsc Ecol. 2009; 24:611–628. DOI: 10.1007/s10980-009-9337-9

Tomscha SA, Gergel SE. Ecosystem service trade-offs and synergies misunderstood without landscape history. Ecol Soc. 2016; 21doi: 10.5751/ES-08345-210143

Tscharntke T, Klein AM, Kruess A, Steffan-Dewenter I, Thies C. Landscape perspectives on agricultural intensification and biodiversity—ecosystem service management. Ecol Lett. 2005; 8:857–874. DOI: 10.1111/j.1461-0248.2005.00782.x

Vacquie L, Houet T, Sohl T, Reker R, Sayler K. Modelling regional land change scenarios to assess land abandonment and reforestation dynamics in the Pyrenees (France). J Mt Sci. 2015; 12:905–920. DOI: 10.1007/s11629-014-3405-6

Vannier C, Byczek C, Crouzat E, Lasseur R, Cordonnier T, Longaretti P-Y, Lavorel S. Cartographier les Services Écosystémiques: quelles données, quels modèles, quelles échelles? Exemple autour du bassin de vie de Grenoble. Environnement Urbain / Urban Environment. 2017; 11

Verhagen W, Van Teeffelen AJA, Baggio Compagnucci A, Poggio L, Gimona A, Verburg PH. Effects of landscape configuration on mapping ecosystem service capacity: a review of evidence and a case study in Scotland. Landsc Ecol. 2016; 41:1457–1479. DOI: 10.1007/s10980-016-0345-2

Wu JG, Shen WJ, Sun WZ, Tueller PT. Empirical patterns of the effects of changing scale on landscape metrics. Landsc Ecol. 2002; 17:761–782. DOI: 10.1023/A:1022995922992

Zimmermann P, Tasser E, Leitinger G, Tappeiner U. Effects of land-use and land-cover pattern on landscape-scale biodiversity in the European Alps. Agric Ecosyst Environ. 2010; 139:13–22. DOI: 10.1016/j.agee.2010.06.010

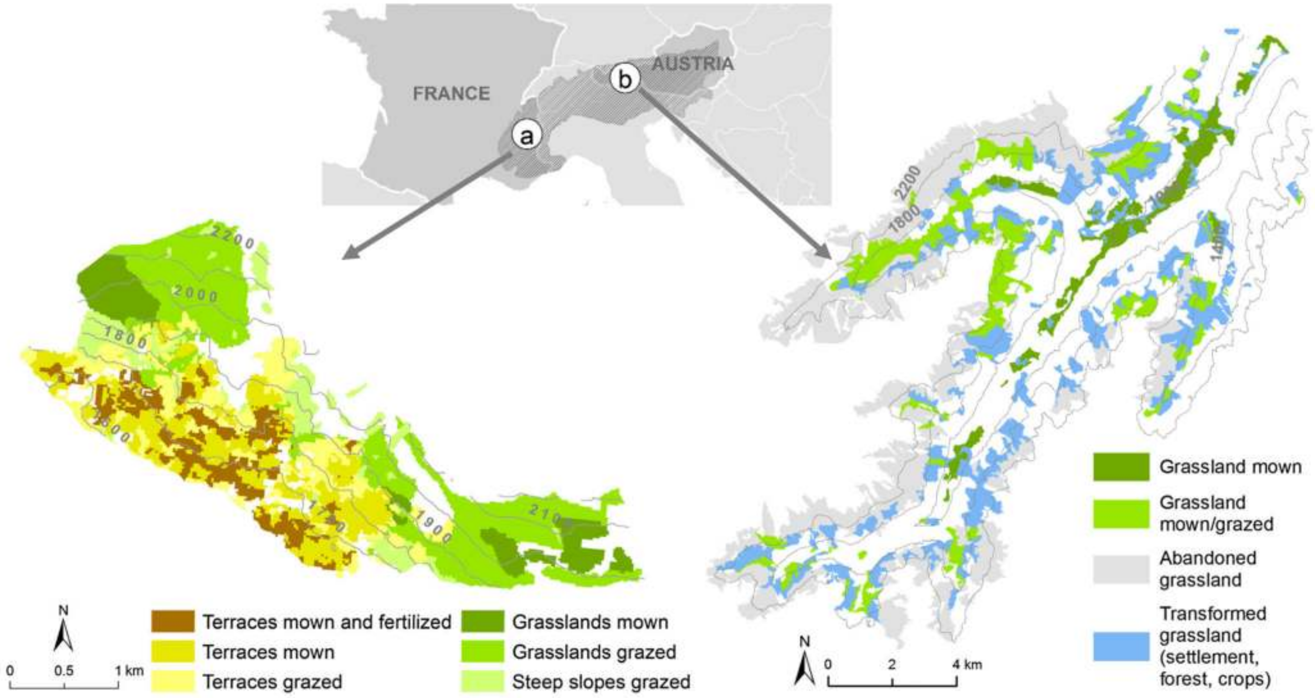

Fig. 1.

Location of the study sites in the Alps. **a** Lautaret in the Upper Romanche Valley, France. **b** Stubai in the Stubai Valley, Austria. Current grassland management including historically managed but now transformed grassland areas for the Stubai site. The areas depicted in *white* represent areas never used as grassland (i.e. rocks, forest)

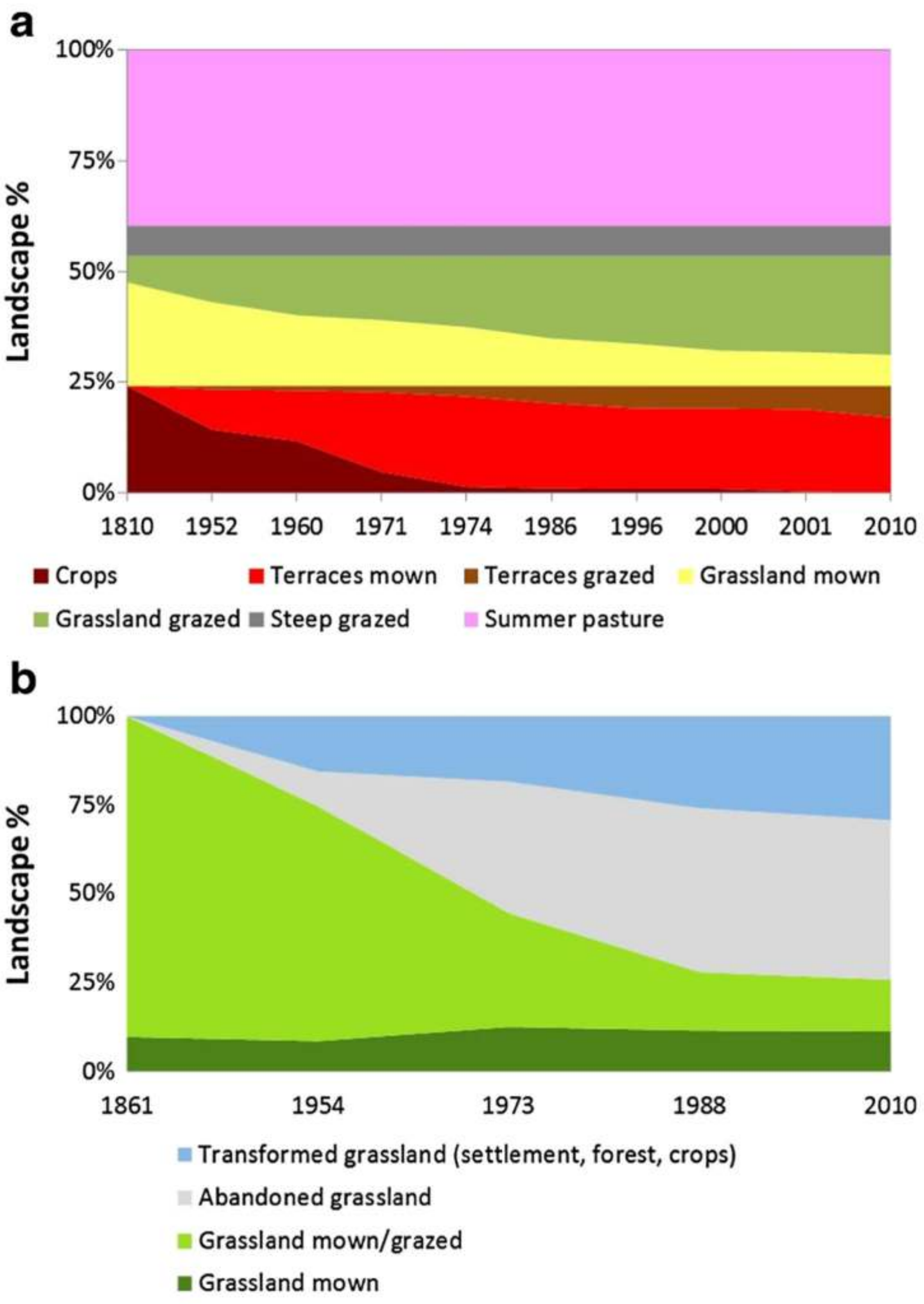

Fig. 2.

Historical land use trajectories for **a** Lautaret and **b** Stubai

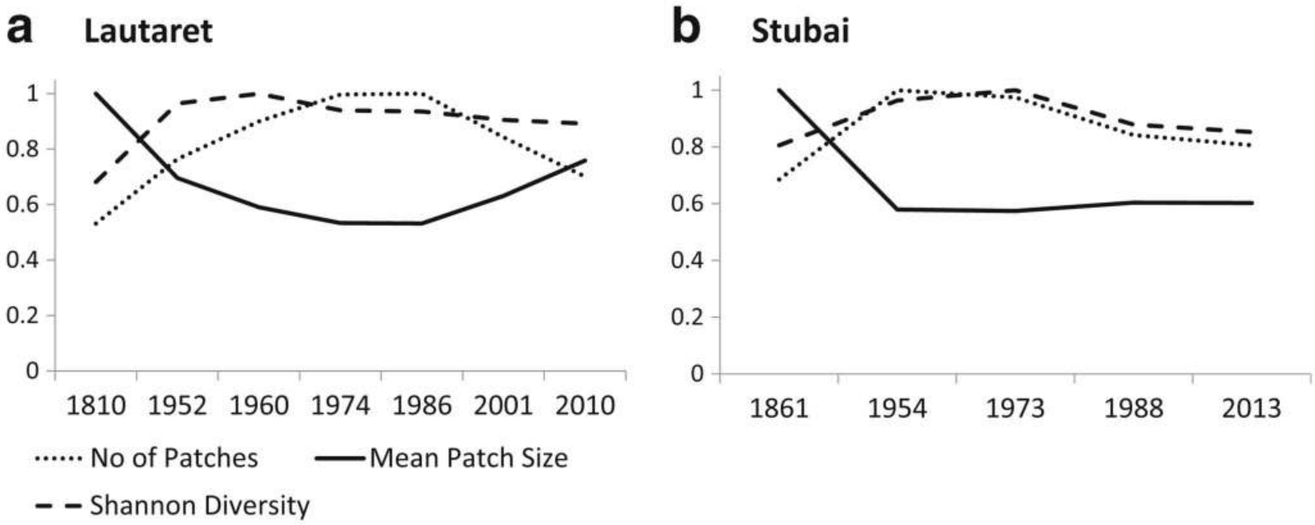

Fig. 3.

Historical trajectories for landscape diversity (Shannon index) and patch number and mean size for **a** Lautaret and **b** Stubai. All variables are standardised 0–1

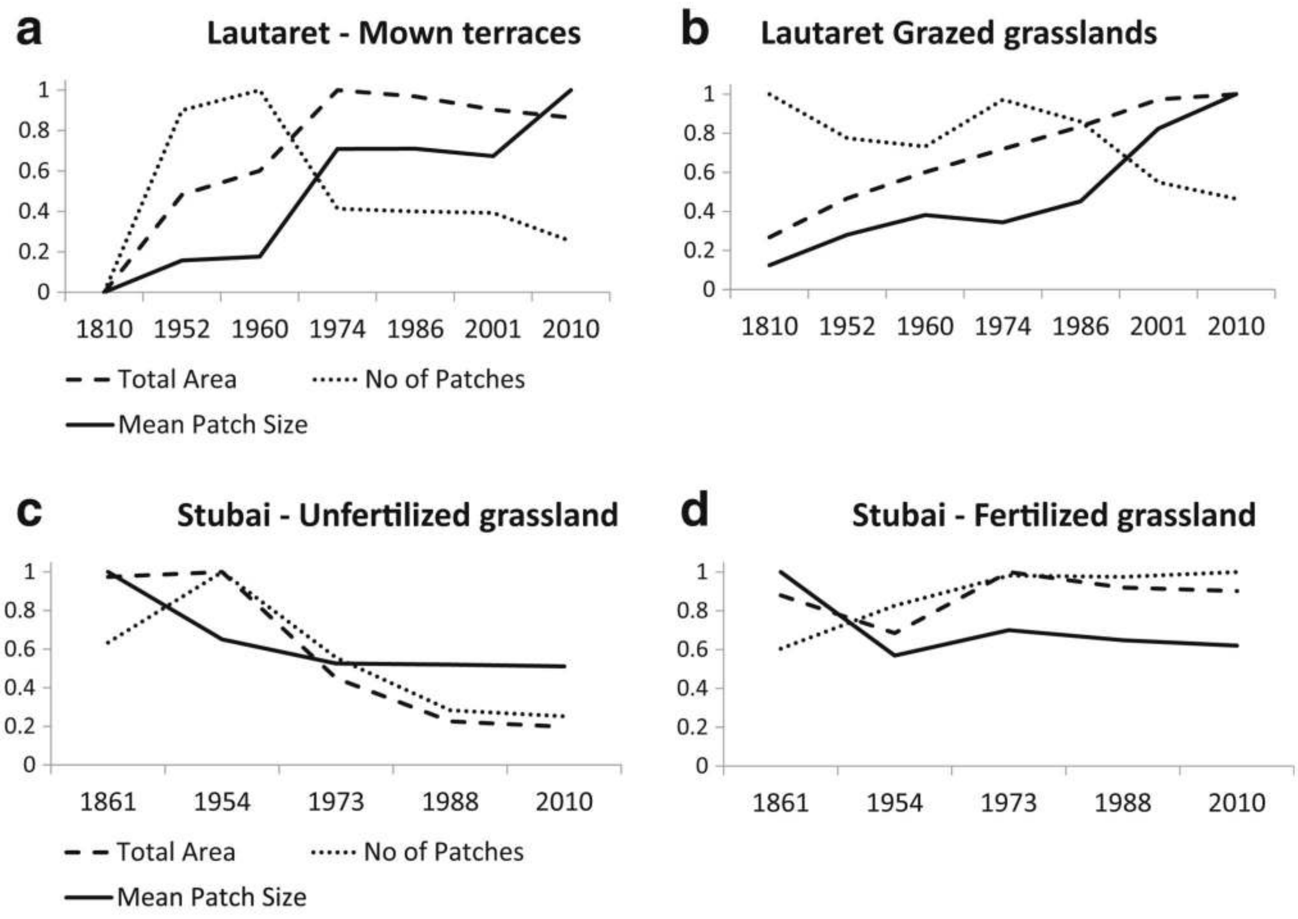

Fig. 4.

Historical trajectories for total area, patch number and mean patch size for specific management trajectories with high management stakes. **a** Lautaret mown terraces. **b** Lautaret grazed Festuca grassland. **c** Stubai unfertilized grassland. **d** Stubai fertilised grassland. All variables are standardised 0–1

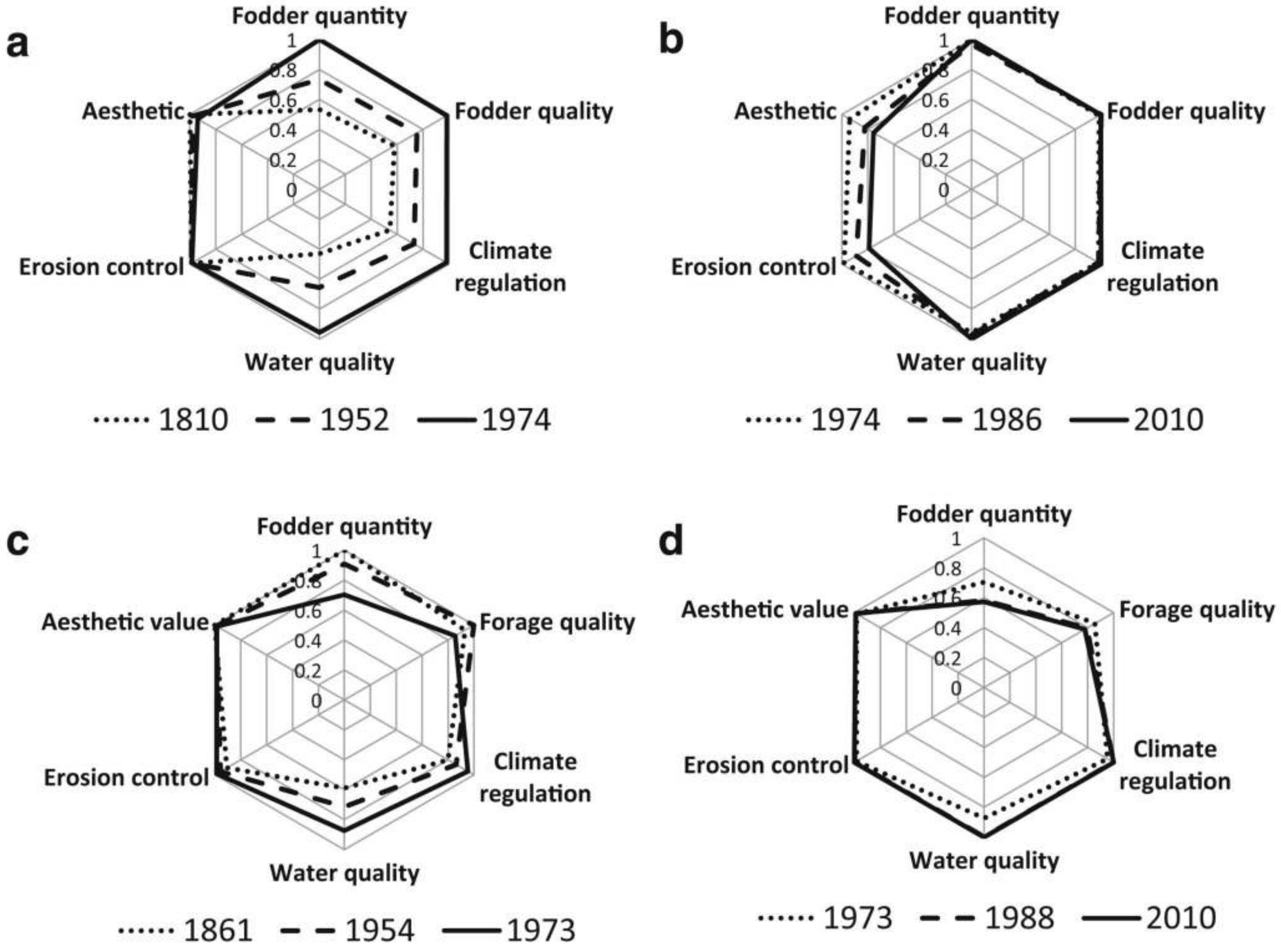

Fig. 5.

Spider diagrams of ecosystem services for **a** Lautaret 1810–1974, **b** Lautaret 1974–2010, **c** Stubai 1961–1973, **d** Stubai 1973–2010

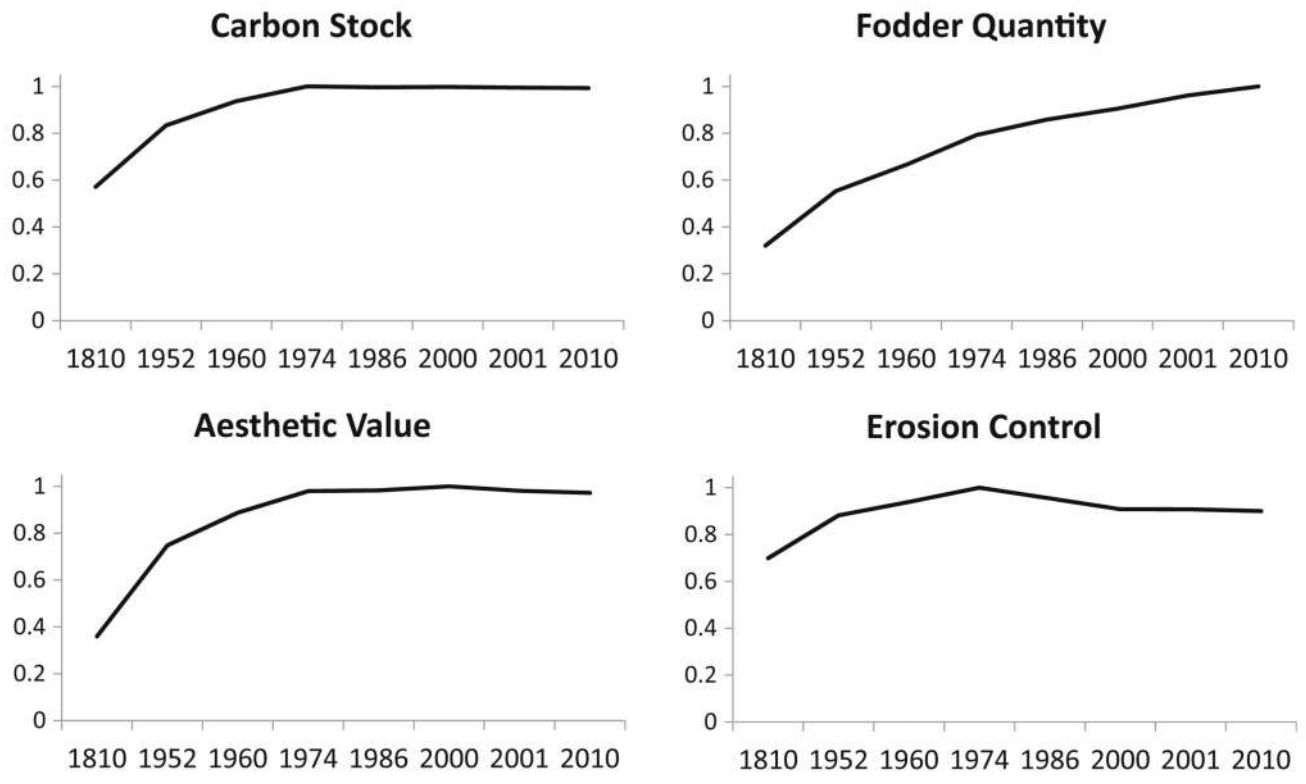

Fig. 6.

Historical trajectories for landscape weighted variance in individual ecosystem services at Lautaret. Values for individual ecosystem services are standardised to a maximum value of 1

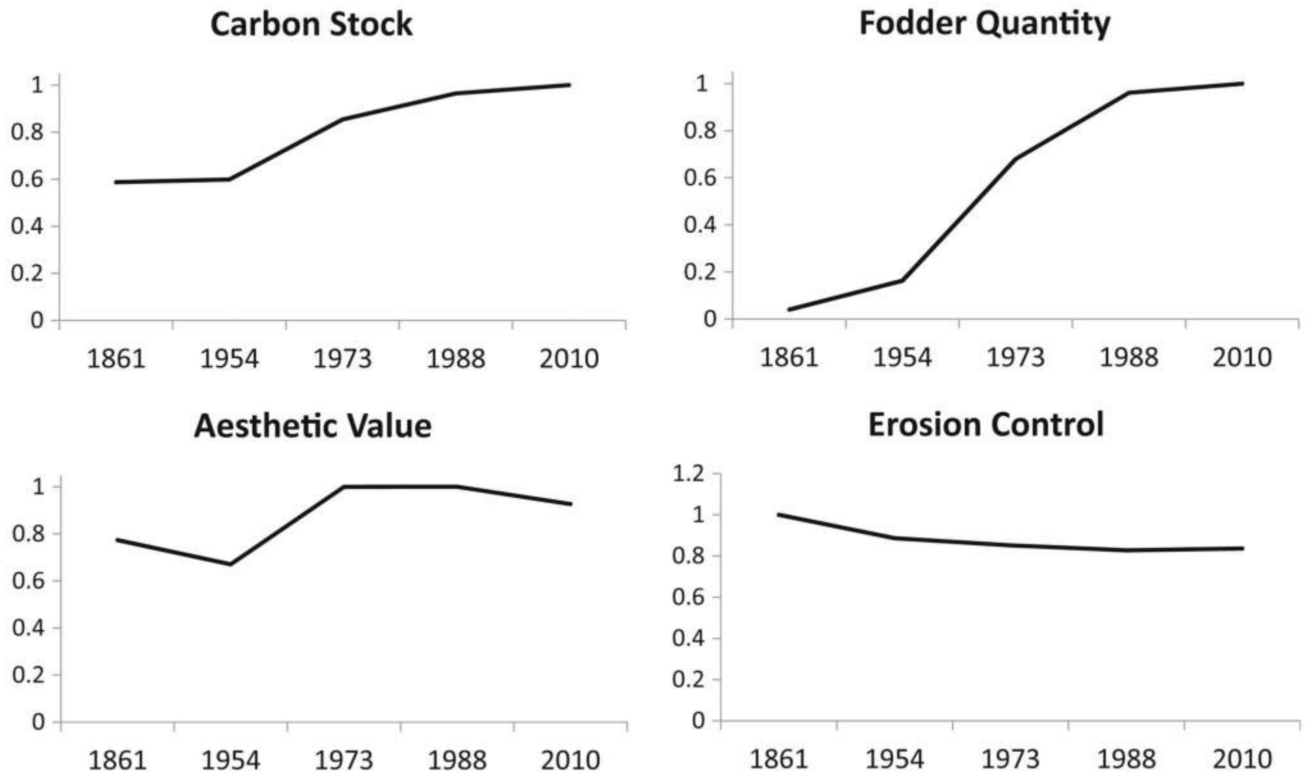

Fig. 7.

Historical trajectories for landscape weighted variance in individual ecosystem services in Stubai. Values for individual ecosystem services are standardised to a maximum value of 1

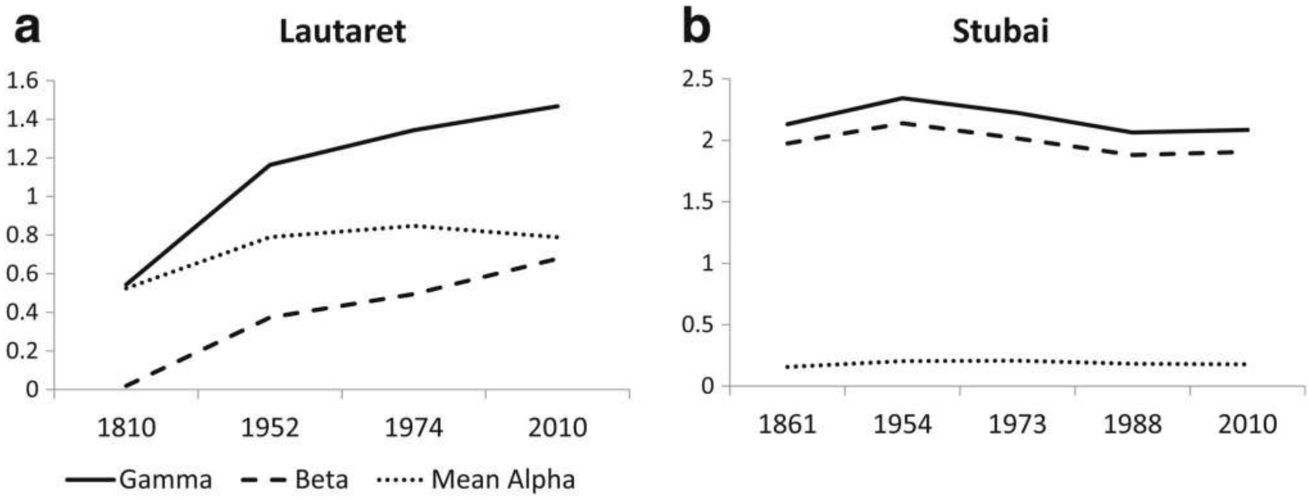

Fig. 8.

Historical trajectories for landscape diversity in ecosystem services, including mean patch-level α-diversity, β-diversity (inter-patch turnover) and γ-diversity (overall diversity). All indices are Shannon diversity. **a** Lautaret. **b** Stubai

Table 1

Ecosystem service indicators and summary of parameters for ecosystem service models at plant community scale

Ecosystem service	Indicator	Model parameters	Reference
Fodder production	Peak biomass production	Soil water holding capacity Community mean leaf nitrogen concentration, community mean vegetative height	Lavorel et al. 2011
Fodder quality	Fodder crude protein content	Soil water holding capacity Community mean leaf dry matter content, community mean vegetative height	Lavorel et al. 2011
Climate regulation	Soil carbon stock	Soil total nitrogen, soil nitrate concentration Community mean leaf nitrogen concentration	Grigulis et al. 2013
Water quality regulation	Leached nitrate	Soil pH, soil nitrate concentration	Grigulis et al. 2013
Maintenance of soil fertility	Nitrogen mineralisation potential	Soil total nitrogen, soil nitrate concentration Community mean leaf nitrogen concentration	Grigulis et al. 2013
Erosion control	Plant rooting pattern	Community mean root density	Tasser and Tappeiner 2005
Aesthetic value	Amount and diversity of flowering	Number of flower colours, total community flowering duration, total abundance of flowering species, Simpson diversity	Schirpke et al. 2017