PUBLICATION INFORMATION

This is a pre-print version of an article by Lavorel, S.; Colloff, M.J.; Locatelli, B.; Gorddard, R.; Prober, S.M.; Gabillet, M.; Devaux, C.; Laforgue, D.; Peyrache-Gadeau, V.. 2019. **Mustering the power of ecosystems for adaptation to climate change**. *Environmental Science and Policy, 92:87-97*.
DOI: https://doi.org/10.1016/j.envsci.2018.11.010

Mustering the power of ecosystems for adaptation to climate change

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Abstract

Mountain social-ecological systems (SES) supply important ecosystem services that are threatened by climate change. In mountain SES there is a paradox between high community capacity to cope with extremes, and governance structures and processes that constrain that capacity from being realised. Climate adaptation maintaining livelihoods and supply of ecosystem services can catalyse this innate adaptive capacity if new adaptive governance arrangements can be created. Using the French Alps as a case study, we outline a participative framework for transformative adaptation that links adaptive capacity and governance to provide social innovation and ecosystem-based adaptation solutions for mountain SES. Grassland management was the main entry point for adaptation: bundles of adaptation services supplied by the landscape mosaic of biodiverse grassland types can maintain agricultural

production and tourism and facilitate income diversification. Deliberate management for core adaptation services like resilient fodder production, erosion control, shade or aesthetic value generates co-benefits for future transformation ability. People activate bundles of adaptation services along adaptation pathways and realise benefits via co-production with other forms of capital including traditional knowledge or social networks. Common and distinctive adaptation services in each pathway create options for transformation if barriers from interactions between values and rules across scales can be overcome. For example conserving mown terraces which is a critical adaptation nexus reflects a complex interplay of values, markets and governance instruments from local to European scales. We conclude that increasing stakeholders capacity to mobilise adaptation services is critical for empowering them to implement adaptation to global change.

1. Introduction

Mountain social-ecological systems (SES) supply abundant and diverse ecosystem services to people within and beyond mountain regions (Grêt-Regamey et al., 2012). Land use, shaped by long-term co-adaptation of humans and ecosystems to environmental drivers, directly controls ecosystem service supply capacity (Quétier et al., 2007b), and ecosystem service flows (Egarter Vigl et al., 2017; Locatelli et al., 2017). But mountain SES are now exposed to unprecedented climate change (Gobiet et al., 2014), jeopardizing ecosystem services. Mountain SES are sensitive to multiple climate-driven stressors including increasing temperature, and frequency and intensity of natural hazards (e.g. floods, droughts, avalanches) along with changes in land use (Briner et al., 2013; Locatelli et al., 2017; Nogués-Bravo et al., 2007). Market pressures and economic policies historically have driven, and continue to drive, structural changes in agriculture in mountain SES, amplifying land-use contrasts: in particular, marginal agricultural land has been abandoned or re-forested, whereas agriculture has intensified in favourable areas (Jepsen et al., 2015). Both types of change combine increasing and decreasing effects on biodiversity and ecosystem services (Egarter Vigl et al., 2017; Locatelli et al., 2017).

Historical and current dynamics of mountain SES reveal a key paradox that shapes options for societal adaptation to global change. From a resilience-vulnerability viewpoint, there is a generic trade-off between adaptation to short-term threats, which may result in actions that increase vulnerability in the long-term, and long-term adaptation responses which may discount short-term needs (Maru et al., 2014). For example in mountains, current climate adaptation of winter tourism through snow making prevents long-term thinking and engagement to find alternative options, while compromising water resources and biodiversity. Conversely, foregoing this technological option and choosing to develop softer tourism may incur a risky economic transition. This trade-off is exacerbated in remote communities by dependence on uncertain natural resources, limited economic options due to biophysical constraints and distance from markets, difficulties in accessing public services and decision makers, and reliance on government subsidies. Throughout history, mountain ecosystems were buffered from biophysical change by their topographic complexity and glacial dynamics (Randin et al.,

2009; Scherrer and Körner, 2010). Mountain people have adapted to live in extreme, variable environments (von Glasenapp and Thornton, 2011). But now, rapid climate change and resulting ecological shifts and increased natural risks, synergised with external policy and market pressures and detachment from governance structures and processes have marginalized communities and reduced their adaptive capacity (Gentle and Maraseni, 2012; Ingold et al., 2010)). However, mountain SES are also foci of social innovation to address global change, with, for example, fresh approaches to niche marketing and Geographical Indication of products (Lamarque and Lambin, 2015), development of novel energy-neutral buildings or new forms of nature-based tourism and education (Bourdeau, 2009). As such they demonstrate exemplary cases of adaptation that can be considered as "seeds for a good Anthropocene" (Bennett et al., 2016).

A key challenge for mountain SES, and our goal here, is to identify pathways for transformative adaptation under severe climate change. Such pathways require reconfiguration of local economies which capitalizes on, and enhances historical resilience to biophysical change and political-economic impacts; builds on natural and social capital, and specifically increases sustainable use of mountain ecosystem services. Such nature-based solutions (NBS) to climate change link societal dependence on ecosystems with biodiversity benefits as components for adaptation (Maes and Sanders, 2017). Yet, operationalization of nature-based solutions is still in its infancy, and it will only improve with stronger conceptual frameworks tested through practice (Nesshöver et al., 2017).

One such framework is adaptation pathways for "exploring and sequencing sets of possible actions based on alternative, uncertain developments over time" (Wise et al., 2014). Adaptation pathways reveal critical elements for transformative adaptation by focusing on the dynamics of the focal SES and possible adaptation responses. An adaptation pathways approach is well suited to informing NBS because it enables social learning, experimentation, scenario planning and livelihood innovation

where goals are ambiguous, decisions are contested, systems are highly dynamic and change is unpredictable.

The framework developed by the Transformative Adaptation Research Alliance (TARA) (Colloff et al., 2017) operationalises adaptation pathways (Wise et al., 2014) by combining adaptation services (AS) (Lavorel et al., 2015) and the values-rules-knowledge (VRK) perspective to influence decision contexts for adaptation (Gorddard et al., 2016).

Adaptation services, defined as the benefits people derive from the capacity of ecosystems to moderate and adapt to the effects of climate change, reveal novel benefits to people from the capacity of ecosystems to persist and supply existing services, or to transform and supply new ones (Colloff et al., 2016b; Lavorel et al., 2015). For example, afforestation of slopes buffers risk of landslides from extreme rainfall; plant functional diversity buffers against new disturbances such as more frequent wildfires. Complementary to nature-based solutions (NBS; (Cohen-Shacham et al., 2016)), adaptation services highlight that when transformation of some ecosystems under climate change is inevitable, pro-active management and governance can facilitate the creation of new benefits for people. For example, restoration of landscape connectivity that facilitates species migration can support future benefits from novel ecosystems such as new pastoral systems in drought-impacted agricultural landscapes of south-eastern Australia (Prober et al., 2017). Adaptation services thus entail co-production of future nature values for people by active and early anticipation of climate change impacts and by mobilising the required knowledge, social and material capital to enable the realisation of benefits from those services.

Therefore, for adaptation services to be co-produced and provide future livelihood options, new decision contexts are needed, that shift the prevailing values, rules and knowledge of decision makers (Colloff et al., 2016a). The VRK framework (Gorddard et al., 2016) enables analysis of how the evolving

socio-ecological system shapes the context of future adaptation decisions. Developing knowledge of the above adaptation services for instance, may shift preferences and world views, potentially triggering support for changing rules and governance systems (Ahvenharju et al., 2018). For transformative adaptation in mountain SES, shifts in knowledge, norms, preferences, and world views will drive changes to current rules and governance. Adaptation pathways are a way of planning and implementing such transformations (Butler et al., 2015). For example the analysis of adaptation pathways for agricultural landscapes of south-eastern Australia expected to become warmer and drier under climate change, revealed that value constraints would be difficult to address, whereas those based on rules or knowledge would be amenable to group and higher level planning and policy (Prober et al., 2017).

Adaptation pathways can be developed by stakeholders identifying visions of their desirable future, including statements of desires, assumptions and beliefs (Myers and Kitsuse, 2000). Visions differ from scenarios in that they are normative and do not forecast effects of a priori drivers on ecosystems, and well-being (Rosa et al., 2017). As visions depend on the plurality of values assigned by individuals, based on their personal experiences, memory and preferences, stakeholders can generate collective visions through deliberation and co-learning processes (Kenter et al., 2016). Visions with ecosystem services have been co-produced in Romania (Hanspach et al., 2014) and Spain (Palomo et al., 2011). Several authors applied exploratory scenarios combining climate and socio-economic drivers for European mountain regions (Briner et al., 2013; Lamarque et al., 2014a; Schirpke et al., 2017) but participatory visioning has not yet been widely used or documented in adaptation science projects, but is gaining interest (Butler et al., 2015).

Herein, we used the TARA framework to examine the key conditions to support transformative adaptation for an SES in the French Alps that has undergone recent climate and concomitant socio-economic changeand adaptation. We developed visions and adaptation pathways, using existing

knowledge and community participation. We quantified bundles of adaptation services mobilised by different adaptation pathways, identified their contributions to transformative adaptation, and analysed elements of the decision context for transformation.

2. Methods

We analyzed adaptation pathways and services for a mountain SES using four steps, updated from those of (Lavorel et al., 2015).

2.1. SES characteristics

Lautaret, in the upper Romanche valley (45.03 °N, 6.24 °E), is part of the Central French Alps long-term socio-ecological research (LTSER) site (Lavorel et al., 2013), covering 45 km² at 1300–3900 m.a.s.l. Climate is alpine with Mediterranean influences (mean minimum temperature -7.4 °C [February], mean maximum temperature 19.5 °C [July]; annual precipitation 956 mm; 60% as winter snowfall; growing season: mid-April to mid-October). The landscape is shaped by livestock farming, with grasslands dominating south-facing slopes. Trajectories of grassland management were identified from historical and current management (Lavorel et al., 2017), summarised in a state-and-transition model (Quétier et al., 2007b) (Supplementary Fig. 1 Fig. 1). Three altitudinal bands represent different land use histories, within which transitions between states are determined by current management (Kohler et al., 2017): terraces (hay meadows, with or without fertilisation, or grazed in spring/autumn; 1300–1900 m.a.s.l.), historically mown grasslands dominated by tussock grass Patzkea paniculate (P. paniculata grasslands henceforth, currently mown or grazed in early summer; 1900–2200 m.a.s.l.) and alpine summer pastures (under grazing for several centuries, 2200–2700 m.a.s.l.). Since the 1970s overall management intensity has been declining with gradual conversion from mowing to grazing and decreasing fertilization of mown terraces (Lavorel et al., 2017). Terrace cultivation (until the late 19th century), fertilization, mowing and summer grazing shape plant composition, plant functional traits; and ecosystem function and services (Grigulis et al., 2013; Lavorel et al., 2011, 2017; Quétier et al.,

2007b). North-facing slopes have Larix decidua and Pinus uncinata forest below 2150–2200 m.a.s.l., with sparse vegetation, rocks and glaciers at higher altitude.

The social system of major actors, governance and economic activities centres on the municipalities of La Grave and Villar d'Arêne, with 800 permanent and 400 temporary residents. Farming systems are still traditional and typical of high mountains, with fodder self-sufficiency and summer transhumance. The analysis of farming system governance emphasized the role of collective institutions and subsidies (Schermer et al., 2016). Tourism has been increasingly important at La Grave since the 1970s (skiing, hiking, climbing), though is less intensive than at nearby resorts. Tourism is also an essential component of the local economy by providing off-farm employment and income.

2.2. Visions

Synthesis of long-term ecological and social research at the site since 2003 formed a basis for visions and adaptation pathways analysed in this study. Previous exploratory scenarios were developed considering alternative combinations of climate change severity (downscaled IPCC SRES scenarios or alternative levels of drought frequency) and socio-economic context (especially in terms of markets and agricultural subsidies), and involving local and regional stakeholder participation. Through modelling they described spatially-explicit impacts on farming systems, ecosystems (plant composition, biomass production and carbon and nitrogen cycling functions) and their services by 2040–2050 (Lamarque et al., 2013, 2014a; Quétier et al., 2007a). These scenarios highlighted the role of agri-environmental subsidies, geographical designation and local markets for sustaining livestock farming and its adaptation to increasing droughts by moderate intensification of hay production or grazing. In the absence of subsidies mowing stopped and, in the most extreme cases local farms ceased operating while external enterprises managed grasslands for biodiversity and/or livestock production. To broaden perspectives and incorporate transformative elements under an assumed worst case climate scenario (RCP8.5), these downscaled scenarios were complemented by the

Montagne 2040 scenarios developed by the Rhône-Alpes region which considered extreme economic liberalization or nature conservation (Centre Economique, 2013), and by insights from other southern European mountains (Italy, Greece).

We enriched this synthesis using observations, interviews and workshops in 2016. First, following closure of the access road for six months by a landslide at Chambon Tunnel, we conducted 2-hour structured interviews (January-May 2016) with fifteen local informants. Informants were identified in collaboration with the informal collective coordinating public action and communication since June 2016, and complemented through local contacts. They included one farmer (Male), national park staff (one officer Female, one ranger M), one mountain guide (M), hospitality professionals (2F), one tourism professional (M), one doctor (F), one social worker (F), one self-employed (M), one taxi driver (F) mayors and their adjuncts (4; 3M, 1F), one member of parliament (M). Informants were asked to describe impacts of the road closure on their livelihoods, activities and linkages. After describing elements of their place attachment, informants spontaneously addressed how the crisis led them to question the effectiveness of current governance and their individual and collective values. They always ended reflecting on the future of the place, given major economic challenges (Bally et al., 2017).

Second, in July-August 2016, we conducted in depth interviews (ca. 2 h) with 14 key informants: farmers (2M), national park staff (one officer F, one ranger M), mountain guides (2M), tourism professionals (1M, 1F), hospitality professionals (3F), agricultural experts (1M, 1F), and tourism (1M) and natural risks (1M) scientists. They were asked about their visions of economic activities, land use (from agriculture and tourism) and the landscape, and about constraints and opportunities for reaching these visions. Finally, in September 2016 to complement largely male-dominated informant interviews we workshopped visions with seven women of diverse ages (35–63), time of residence (born there, >20 years, <10 years), professions and education. Interviews were supported by

observations and informal conversations, and comments therein on visions and decision contexts were documented by the first author.

2.3. Adaptation services

Adaptation services provide the potential for people to adapt and reach visions based on biodiversity and ecosystem functioning (Colloff et al., 2016b; Lavorel et al., 2015). We identified and quantified adaptation services, including (i) ecological properties that support the persistence of current ecosystems and their services, (ii) latent ecosystem services (ES) (not currently used but of value for adaptation) and (iii) ecological properties that underpin ecosystem transformative capacity which facilitates (iv) increased supply of previous ES (e.g. through colonization by more productive species) or (v) novel ES emerging from new biophysical and social contexts (Colloff et al., 2016b). We used visioning interviews and workshops (see above), our previous spatially-explicit projections of scenarios of climate and social-economic change (Lamarque et al., 2013, 2014a; Lamarque et al., 2014b; Quétier et al., 2007a), analyses of summer pasture social-ecological resilience (Nettier et al., 2017) and our prior analyses of ecological resilience (Kohler et al., 2017) to hypothesize adaptation services for each vision. We then quantified these adaptation services for each grassland management type using trait-based models of current ES (Grigulis et al., 2013; Lavorel et al., 2011) and ecosystem resilience models (Kohler et al., 2017).

2.4. Adaptation pathways and VRK analysis

We constructed adaptation pathways as courses of action to reach visions from the current SES according to biophysical and social drivers of change. Adaptation pathways were characterized by critical time windows where agency plays out to inflation the SES trajectory towards a given vision, which we refer to as ‘windows of agency' (WA). WA may be discrete periods associated with crises or

tipping points and critical decision points, or extended periods of gradual change and cumulative, incremental decisions. Ecological potential for adaptation is activated by actors along pathways, thereby enabling adaptation services. In our analysis we identified adaptation services deliberately managed for adaptation (Colloff et al., 2017; Lavorel et al., 2015), additional services derived as co-benefit from these deliberate adaptation services, and also those adaptation services that emerge during pathways as co-benefit from adaptation to other drivers (e.g. changes in economic context).

Decision contexts for each WA in a pathway are determined by interactions of prevailing values, rules and knowledge (VRK) used by decision makers. In the VRK model, 'values' refer to basic human ('held') values that determine goals and world views and prompt actions and preferences; 'rules' are the conventions that prescribe or proscribe actions, including laws and social-cultural norms for how rules are interpreted and applied and 'knowledge' includes local, experiential and tacit and knowledge as well as scientifics and technical knowledge, predictions and data (Colloff et al., 2018; Gorddard et al., 2016). The analysis of VRK helped us understand barriers, enabling factors and required changes to adaptation decision-making for the mobilization of suggested

adaptation services within adaptation pathways (Colloff et al., 2016a; Prober et al., 2017).

We constructed pathways towards stakeholder visions and used the VRK approach for analyzing decision contexts. Workshop and interview transcripts were scored for constraints and opportunities at each WA and the values, rule and knowledge issues applicable to each WA were identified and catalogued. We assessed values, rule and knowledge constraints and enablers separately and in combination (i.e. the interactions among VR, VK, RK and VRK) (Prober et al., 2017). For example, the values of place attachment associated with traditional land management can create a values-knowledge interaction around resistance to change and innovation. However, revitalisation of traditional practices may have considerable adaptive value. Similarly, inflaible management subsidy rules create a rules-knowledge interaction by inhibiting the adaptation of traditional practices. But this barrier can be overcome via a VRK interaction whereby rules for subsidies are flexible and locally implemented, allowing resources for extension services to address adaptation knowledge needs.

3. Results

3.1. SES characteristics

The SES (Fig. 1) features strong constraints from climate, steep terrain and natural hazards (landslides, avalanches); characteristics of mountain regions that have been incorporated into land use practices, planning, and culture. Mean annual temperature has increased by 1 °C in the last 30 years and precipitation is more variable (Nettier et al., 2017). Visible climate change impacts are glacier retreat and a shorter snow season, with effects on the diverse flora and fauna including earlier phenology, recolonization of glacier margins and shifts in species distributions. The SES is part of the Ecrins National Park. The two municipalities have joined the Park's charter that encompasses their buffer area, and respectively 64% (Villar d'Arêne) and 10% (La Grave) of their land is within in the core protected area (Parc National des Ecrins Charter, 2013).

Fifteen farms produce lamb, beef, cheese and heifers sold for producing the certifi Beaufort cheese in the nearby Maurienne valley. Transhumant herds (ca. 5000 sheep) from the southern part of the region graze summer pastures. Farm economies depend on agri-environmental subsidies (up to 80% of farm income) and on tourism for off-farm employment and real estate revenue (Schermer et al., 2016). Young local and incoming farmers are replacing retirees. Governance is shaped by regional markets and subsidies: the Agricultural Chamber, the Pastoral extension service and Ecrins National Park are key

agencies. Farmers' collectives manage hay meadows and pastures at Villar d'Arêne. Since 1950, 60% of hay meadows have converted to grazing—a regional trend—but unlike nearby regions land have not been abandoned (Lavorel et al., 2017). Stakeholders identify grassland ES of fodder production, soil fertility and stability, water quality, carbon storage, cultural heritage and scenic beauty (Lamarque

et al., 2011). Fodder production has so far been mainly impacted by increased interannual climate variability, resulting in uncertainty about securing hay stocks and end-of-season grazing. Increased drought risk threatens the persistence of mowing and thus self-sufficiency, challenging the current farming system (Lamarque et al., 2013). La Grave is an international centre for skiing, climbing and sightseeing. Ecrins National Park has >100,000 visitors annually, mostly in summer. Less snowfall already challenges winter activities especially at the beginning of the season and below 2000 m.a.s.l., though La Grave retains a competitive advantage over resorts at lower altitudes. Glacier melt and increasing rockfall risk, along with more frequent heat waves challenge high altitude mountaineering activities. Two famous mountain passes host the Tour de France cycle race and 5000 vehicles pass daily in summer. Demand for tourism has declined overall in recent years. Tourism is controlled by national park regulations and supported by public-private investments and subsidies. Local governance is via the Municipalities, the Mountain Guides and Shopkeepers' associations. Property development is subject to stringent planning rules and bounded within villages. Year-round access is via one main road which connects the SES with neighbouring towns for local administration and health services (30 km away), cultural activities and schooling, and with main regional city centres (100 km away). The SES is at the boundary between two natural and administrative regions, posing a challenge of perceived marginality and offering opportunities for benefit from resources and connections in both regions. (Bally et al., 2017).

3.2. Visions

Four visions were developed on the assumption of worst case climate change (Table 1). We chose to build pathways under worst case climate change considering that preparedness for transformative climate change would build robust options for an uncertain future (Smith et al., 2011). Stakeholders discourses were remarkably convergent, defining the Seeds of Hope vision, which is congruent with political sustainability visions (e.g. Montagne 2040 visions of the Rhône-Alpes; Commission

Internationale pour la Protection des Alpes, CIPRA, for the European Alps) (Lamarque et al., 2013; Quétier et al., 2007a). Ranching was articulated by stakeholders as the most plausible alternative, viewed as the failure of Seeds of Hope, and thus considered as a threat. Stakeholders did not envision spontaneously the other two scenarios: Wild Mountainswhich was proposed regionally by Montagne 2040 (Centre Economique, 2013), and Local Subsistence which was formulated by scientists based other European situations (Italy, Greece). When we suggested those scenarios, stakeholders considered them as unacceptable (Wild Mountains) or remote but interesting (Local Subsistence). (fig 1) (tab 1)

The Seeds of Hope vision conserves what stakeholders perceive to be the best of current SES attributes (e.g. preserved traditional pastoral activity, environmental quality, original form of tourism) while evolving to a more sustainable future via proactive local governance and management that promote non-material quality of life and the iconic landscape. The vision, which extends our previous local development scenario (Lamarque et al., 2013), is achieved by supporting nature conservation and local agriculture, including revived and diversified livestock systems and new horticultural production. There is strong support for 'soft' tourism (i.e. that is environmentally and socially compatible with the SES, for instance agritourism or tourism based on health or spiritual benefit from wild foods and the mountain environment), requiring diversification and limited new infrastructure to respond to climate change.

Ranchingwas analysed in our previous exploratory studies as a combination of severe climate change and globalised economy (Lamarque et al., 2013; Quétier et al., 2007a), and portrayed in Montagne 2040 as neoliberal development. In Ranching, local livestock systems are replaced by transhumant stock on summer pastures, controlled by external enterprises. Mowing ceases, terraces decay, trees and shrubs encroach and mass tourism develops, with associated infrastructure.

Local Subsistence involved ex-urban or foreign migrants in search of available land and self-sufficient livelihoods, with intensive agriculture: livestock intensification via increased fertilization, irrigation

and pasture sowing, new horticulture, terrace restoration and return of cropping. Local Subsistence thus shares agricultural uses with Seeds of Hope, but is underpinned by quite different social motivations. In contrast to Seeds of Hope tourism disappears and nature protection declines.

Wild Mountains, portrayed in Montagne 2040 regional visions as extreme environmental policy, involves cessation of farming and tourism, but was here considered most likely as an outcome of economic failure and emigration. Information on this vision was more limited given that, although it was presented by regional experts as an extreme scenario, no stakeholder formulated it spontaneously, nor thought it possible when asked in interviews. It involves extensive rewilding: forest recolonization (facilitated by climate warming), and increases in populations of large ungulates, raptors and top predators (wolf and lynx).

3.3. Adaptation services

Adaptation services are primarily those ecosystem properties that are deliberately planned and managed for adaptation (Colloff et al., 2017; Lavorel etal., 2015). For instance, in Seeds of Hope and Local Subsistence novel provisioning and cultural ES are mobilized to support diverse livelihoods. Persistence of fodder production is ensured by maintaining drought-resilient vegetation and promoting vegetation that responds to good years, and the latent ES of shade for stock in managed larch meadows becomes valued (Supplementary Table 1; Fig. 2 Fig. 2).

Other adaptation services arise as co-benefit from this management for adaptation. In Seeds of Hope, proactive management for fodder promotes adaptation services that underpin its resilience: soil water retention in fertilized hay meadows on terraces due to increased soil organic matter; landscape connectivity within P. paniculata grasslands and within summer pastures. Latent regulating ES of carbon storage and water quality are also co-benefit from management for drought-resistant fodder production. Hay meadow management promotes connectivity (by consolidating mowing blocks) and plant beta-diversity, and thereby capacity for transformation of grassland composition (Kohler et al.,

2017). Lastly, adaptation services derive from managing drivers other than climate: in Seeds of Hope and Ranching, the latent ES of shade for stock stems from extensive grazing or land abandonment due to changes in policies and markets.

Grassland management is thus the main entry point for adaptation: bundles of adaptation services supplied by different grassland types are identified and can be managed for. Critical adaptation services of resilience of fodder production, erosion control, aesthetic value and plant and animal biodiversity conservation are highly responsive to management, especially on terraces (Fig. 2). This entails agency for these adaptation services, also emphasizing transformative capacity across grassland states (within terraces or within P. paniculata grasslands) as a key adaptation service. In contrast, carbon storage and water quality regulation are determined by land use histories (cf. differences between terraces and P. paniculata grasslands), with their value as latent ES revealed only in Seeds of Hope and Ranching where their demand is supported by social context.

Fertilized hay meadows can be managed for multiple adaptation services: abundant, high-quality, resilient fodder production due to soil water retention in the growing season; with co-benefit of high erosion control, aesthetic value and biodiversity conservation. Their connectivity is however constrained by the trade-off between consolidating continuous blocks of parcels and limitation of mechanisation by terrain. Their conversion to grazing limits these adaptation services, but the good transformative capacity of grazed terraces provides responsiveness to management interventions for restoring mowing and associated adaptation services. (fig 2)

Grazing P. paniculata grasslands supports highly resilient fodder production due to inherent functional properties of the dominant species (Benot et al., 2014), high landscape connectivity, carbon storage and water quality regulation; with benefits likely supplied over the long-term under more severe climate change. These adaptation services trade-off with poor aesthetic value and erosion control. Summer pastures supply moderately resilient fodder production, and their grazing at stocking rates adapted to climate variability supports high connectivity, carbon storage, aesthetic and biodiversity

values. The renewed use of Larch meadows provides highly valuable shade for stock, moderate fodder production of high resilience, high aesthetic value and carbon storage.

3.4. Adaptation pathways

We synthesized adaptation pathways based on climate and social and economic changes that determine conditions for realizing each vision (Fig. 3). We constructed narratives focusing on windows of agency (WA) and how adaptation services identified from previous scenarios and our analyses of ecological potential are mobilised by stakeholders in their discourses (Supplementary Table 2). Pathways provide a framing for the detail of VRK interactions at each WA. As such, these fi pathways were proposed by researchers, but were not yet co-designed with stakeholders. (fig 3)

Currently, at WA1 greater climate variability increases uncertainty of fodder production for wintering stock. Adapting management toward Seeds of Hope requires diversification of agriculture and tourism supported by novel adaptation services, adaptive grassland management for resilient fodder production, including fertilisation of hay meadows and reducing stock densities in years of extreme dry conditions.

As climate change intensified WA2 is an inflation point between Seeds of Hope and Ranching. Fodder supply and winter tourism become more uncertain, but demand for summer tourism increases. In Seeds of Hope, according to stakeholders, the diversified economy supported by values such as sense of place and willingness to maintain local livelihoods is sustained by niche marketing of mountain agricultural products and ‘soft’ tourism. Payments for ecosystem services (PES) support latent regulating services to remote beneficiaries outside the SES (e.g. for carbon storage and water quality). Shade for stock and transformative capacity of hay meadows are highly valued.

If these values, market and institutional conditions are not met at WA2, the SES shifts towards the Ranching pathway. Farmers adopt reverse winter transhumance (sending mountain herds to lower

altitudes in the south of the region), decrease local wintering stock, and respond to strong demand for summer pastures for large herds brought from the south (outside the SES) where climate change strongly impacts on fodder production. Mowing ultimately ceases on permanent grasslands and is strongly reduced on terraces, and summer fodder supply is increasingly uncertain. This shift is initially supported by persistence of the current ES of fodder production by drought-resilient vegetation. Persistence of fodder production from P. paniculata grasslands and summer pastures is an essential adaptation services along with shade for stock on shrub-encroached terraces. As climate change intensified transhumant herders benefit from the transformative capacity of P. paniculata grasslands. Extensive, externally-financed livestock production is supported by global markets, mass tourism and PES for latent regulating adaptation services. A market economy context favours winter resort-based tourism with heavy infrastructure development. Risks of landslides and erosion are addressed with grey engineering.

At WA3 a major economic crisis leading to urban-rural migration and decreased tourism demand creates an inflation towards Local Subsistence: a return to labour-intensive agriculture of the 1970s, with associated adaptation services from fertilized hay meadows and summer pastures. Tourism declines, as does broader social demand for regulating services.

At WA4 the challenge arises of integrating these newcomers working in subsistence agriculture into the local community. Values of flexibility, cultural pluralism and demand for local food products keep the SES in the Local Subsistence pathway. Conversely, failure triggers inflation towards Ranching meeting regional demand for livestock products which cannot be met by diminishing fodder production in the south of the region.

Although not considered by stakeholders who did not spontaneously envision Local Subsistence and the drastic economic and social crisis leading to it, WA5 could be reached after the crisis abates. Actors may decide to return towards Seeds of Hope by redeveloping diversified livelihoods from agriculture and tourism, perhaps using different approaches and options than were available on the initial Seeds of Hope pathway, especially different cultural practices from foreign migrants or new technologies

and social networks from ex-urban migrants. Emerging local values (sense of place re-constructed by newcomers) and the return of favorable economic conditions (urban food markets, summer tourism) would support this inflation, as long as they occur before too extensive landscape transformation and loss of biodiversity.

At WA6 several types of crisis may affect the vulnerable ranching system: successive years of extreme warm, dry conditions drastically impacting fodder supply and snow, wolf predation on livestock, the downturn of market demand for extensively-produced meat or local opposition to external business. Livestock production and winter tourism may then collapse, prompting emigration of younger people, while an aging and economically-disadvantaged population remains in the mountains and the SES shifts towards Wild Mountains. Shrub encroachment and natural hazards transform the landscape. PES support latent regulating AS, biodiversity conservation and afforestation.

WA7 constitutes a final inflation between Wild Mountains or Local Subsistence. Under continuing demographic and economic changes along the Wild Mountains pathway, population density finally falls below a threshold where state government no longer supports infrastructure. Forests reclaim the landscape within new climatic limits. Novel services of game and wolf hunting may emerge, supported by demand from urban populations, and possible demand for biodiversity offsets. Shrub encroachment increases wildfire risk under a warmer and drier climate, so widely-spaced tree species with easily-managed recruitment are valued for their lower fi risk. If however at WP 7 social or economic conditions rekindle demand from urban and/or foreign migrants for mountain farming the SES may be repositioned onto the Local Subsistence pathway, albeit within a reconfigured landscape and SES that comprise a large forested area and reduced agricultural land for a small self-subsistent population.

3.5. VRK analysis

Analysis of windows of agency revealed a rich set of values-rules-knowledge constraints and opportunities (Supplementary Table 2). The pathway to Seeds of Hope (Fig. 4) is constrained by reliance on public subsidies for biodiversity-friendly livestock production and the development of markets and supply chains (R). These rely on societal support and demand; a V-R interaction. The vision of locally-diversifi agriculture and tourism hinges on place attachment and identity, traditional management of a cultural landscape and community solidarity (Hinojosa et al., 2016); values (V) that are reinforced along the pathway. However, evolving governance of subsidies towards results-based measures with local autonomy (Darnhofer et al., 2017) requires support for learning, with key roles for researchers and agencies (R-K interaction). Adaptation of the livestock production system will draw upon grassland resilience and transformative capacity, requiring new knowledge of management options. Strong extension services become vital (R-K interaction), and local resistance to technical innovation must be overcome (V-K interaction). Novel agricultural systems as imagined in Seeds of Hope illustrate cascading VRK interactions, where new initiatives are supported by emerging markets and infrastructure, eliciting needs for locally-adapted knowledge adoption. Continued growth in demand, supported by local values, then leads to mainstreaming of change in the SES.

Pathways toward Ranching have tipping points and 'maladaptive' decisions at WA1 or 2, with a key role for rules. Pathways are initiated by loss of societal values, local control of land tenure and management that sustain Seeds of Hope (V-R interaction). As Ranching unfolds, risks from private land control emerge: urban sprawl, degradation of terraces and summer pastures by out-of-region herds in drought years (R). Risks are enhanced by uncertainty of carrying capacity under climate change, lack of knowledge on grassland adaptation services (K), and cascading effects of lack of interest in local sustainability (V-R-K interaction). Transformation of rules emerges at WA2 with grasslands used for biodiversity offsetting against the impacts of mass tourism infrastructure and private hunting of wolves after loss of protected species status (V-R interaction).

Analysis of leading vs. minor constraints and opportunities and cascading VRK interactions for each pathway (Supplementary Table 2) reveals scales of decision making: 1) farm-scale: decisions on direct

biophysical and management effects; 2) farming and tourism systems: decisions on economic viability and adaptability; and 3) community/society-scale: decisions on strategic adaptation. These embody the three scales of formal and informal institutions (Schermer et al., 2016) for mountain livestock systems. Pathways depict how decision makers navigate between scales and their trade-off and how maladaptation results from tipping point decisions at each scale. Below, we illustrate the interplay between scales for three distinctive issues emerging from the analysis of decision contexts for the seven windows of agency.

First, cross-scale V-R interactions are critical in pathways towards Seeds of Hope, Ranching and Wild Mountains. For example, in Seeds of Hope there is a critical interplay of decisions to maintain mowing and fertilisation of terraces, ensure local farm viability and foster support for collective decision making. (fig 4)

These interactions are threatened by declining support for local values. However, insights on cross-scale VRK interactions by local people during interviews (Supplementary Table 2), and in a dedicated Delphi process (Darnhofer et al., 2017), indicate willingness to engage in local implementation of regional and national policies through collective formal and informal institutions. The pathway to Ranching, refl ing a neoliberal socio-economic model, is typical of a values dissonance between local and national scales, leading to rules with detrimental biophysical impacts (degraded terraces and summer pastures) and loss of social cohesion. However, the Ranching pathway is not inevitable. Failure of grazing and tourism from market downturns and several years of climate extremes could lead to a reframing of social values to initiate transformation toward Wild Mountains; forested landscapes in a depopulated, socially isolated region, with benefi to distant populations from climate mitigation, nature conservation and possibly trophy hunting by rich urban tourists.

Second, adaptation services were not a strong theme in actors' discourses. We found existing uncertainties (e.g. details of grassland transformation under extreme climate, adapted seed mixes or processes of woody colonisation) reflect lack of knowledge integration into management decisions

and strategies for adaptation (Berthet et al., 2018) rather than knowledge defiect per se. Recent resistance to innovation has led to rejection of new options such as equipment for mowing steep slopes and new manure management methods (K–V interaction), but younger farmers, often incomers, may overcome this barrier. At a systems level, scarce resources constrain agricultural extension, local experimentation and learning (K-R interaction). An exception to the limited mobilisation of adaptation services is the 'Sentinel summer pastures programme' (Nettier et al., 2017), initiated by the National Park, the pastoral extension service and networks of managers, scientists, farmers and shepherds for monitoring, knowledge sharing and co-learning about sensitivity and adaptive responses of grasslands to climate variability. Also, regional experts have suggested evolution of the subsidy system to support grassland resilience, rather than just farming or biodiversity (Darnhofer et al., 2017).

Third, livestock predation by wolves is a highly contested issue at the nexus of V-R-K interactions, with critical implications for all adaptation path ways. Wolves are a major constraint on current farm viability and to Seeds of Hope because they challenge extensive herding of large flocks by requiring increased manpower, renewal of shepherding and possibly new technologies. But they also comfort younger farmers in their transformation towards high value-added products (e.g. cheese) that require smaller herds usually kept closer to farms, less mowing and which free up their time, consistent with values underpinning Seeds of Hope. Current international and state rules for wolf conservation are strongly contested reflecting conflicting values, (Chandelier et al., 2018) and indicate a need to reframe rules according to future objectives and associated values. Shifts in values under Local Subsistence or Ranching pathways may allow unregulated wolf control, but declining local community capacity to do so may threaten viability of Ranching. Wild Mountains is rejected by some local or national and European stakeholders based on values around cultural landscapes (Plieninger et al., 2015), but cannot be excluded as a pathway towards regional sustainability (Verkerk et al., 2016); it would require reframing of values to allow niche income from watching and hunting wolves and other

wildlife, and broader knowledge and acceptance of risks and benefi from European-scale land sparing, biodiversity restoration and offsets and associated adaptation services (Pettorelli et al., 2018).

4. Discussion

4.1. Activating adaptation services along future pathways

Our analysis introduces the concept of windows of agency and shows how adaptation services are revealed and activated along adaptation pathways. First, novel ES that can be managed for included provisioning and cultural ES, while latent ES, realized as co-benefi of adaptation or from responses to other drivers, were regulating ES. The value of these regulating ES is currently under-recognised, but increases as climate change intensified (Abson and Termansen, 2011). As a particularly salient example, the value of shade for livestock from transformation to greater tree cover increased in a warmer future as a direct result of upwards tree colonization and as indirect climate effect through land use-related expansion of woody vegetation. Second, changing ES demand

under drier climate turned Festuca paniculata from an undesirable unpalatable grass to a valuable drought resistant resource. Third, intrinsic values of ecological resilience mechanisms that support persistence of current ES and transformative capacity (Kohler et al., 2017; Oliver et al., 2015), such as traits of keystone plants, grassland functional diversity and landscape connectivity, were activated along all pathways. Some knowledge of this resilience is internalised by mountain agrarian societies (von Glasenapp and Thornton, 2011), and is activated by farmers in response to climate variability (Nettier et al., 2017). Though evidence supports high ecological resilience of mountain SES to climate change (Benot et al., 2014), tipping points are poorly understood.

Rather than early phases of climate change adaptation with persistence of current ES and use of latent ES being substituted as climate change intensifi by uptake of novel ES and transformative capacity of

ecosystems (Colloff et al., 2017), our analysis envisioned different adaptation services being cumulatively activated along pathways. Substitution was only evident for the Wild Mountains pathway which entailed a radical transformation of activities, the landscape and associated values and rules (WA7). Here, the adaptation service concept was particularly powerful in highlighting how novel livelihoods can be constructed from transformed ecosystems. We suggest ecological capital for adaptation services is built along each pathway, together with technical, institutional and social-cultural capital required for co-production of adaptation services. Alternatively, loss of critical adaptation services (WA2,7) leads to irreversible ecological change which can turn into path-dependent maladaptation.

Several pathways had common adaptation services: resilience of fodder production in P. paniculata grasslands and summer pastures (in all but Wild Mountains) and in fertilized hay meadows (Seeds of Hope, Local Subsistence), and ecological transformative capacity within each of the three altitudinal bands. These adaptation services are cornerstones of resilience and adaptation, providing multiple future options and ability to shift across pathways (WA5,6). Seeds of Hope and Local Subsistence share novel agricultural adaptation services, with common ecological mechanisms, but adaptation services are embodied differently in each pathway and its decision context. In contrast, adaptation services linked to cultural ES (tourism, biodiversity conservation) were highly specifi to each pathway. Such specifi can initiate path dependencies: loss of biodiversity under Local Subsistence and Ranching form irreversible tipping points from Seeds of Hope. A path-dependent maladaptation cited by stakeholders was the wholesale conversion of terrace mowing to grazing in Ranching (WA4), causing erosion. The grazed terrace plant community is poor at erosion control, inducing a positive feedback of degradation and risks from landslides. In Seeds of Hope, stakeholders know this risk but accept some erosion is likely because maintaining all terraces is not possible.

4.2. Transformative climate adaptation pathways

The TARA approach provides novel results to support local adaptation and adaptive capacity. Five key points emerge. First, by exploring adaptation services and decision contexts, options emerge for stakeholders that were not apparent previously (Berthet et al., 2018; Prober et al., 2017). Most stakeholders were unaware of adaptation options, or of the transformative capacity of ecosystems (Kohler et al., 2017), though these are essential as climate change intensifi (WA2,6). Economic value of the latent ES of carbon storage was deemed adaptive only after co-learning in a role playing game (Lamarque et al., 2014b).

Second, visioning empowers stakeholders to scope adaptation pathways and focus on actions to achieve their vision in accord with their values (Brunet et al., 2018). This transdisciplinary process builds collective understanding and capacity for adaptation (Brown et al., 2016; Hanspach et al., 2014; Palomo et al., 2011). A focus on long-term planning reveals the adaptive value of experience in responding to: climate variability (Lamarque et al., 2013; Nettier et al., 2017), institutional change (Darnhofer et al., 2017; Lamarque et al., 2013), and recent crises (Bally et al., 2017), as seen in other mountain regions (von Glasenapp and Thornton, 2011) and marginalised and remote SES (Fazey et al., 2016; Maru et al., 2014). Such planning al-

(Oteros-Rozas et al., 2014; von Glasenapp and Thornton, 2011), and can be mobilized in pathways.

Third, detailed analysis of adaptation services builds awareness of bundles of services, e.g. farmers and extension officers were only partly aware of the co-benefit of soil moisture retention and plant functional diversity that support resilient fodder production in fertilized hay meadows. Likewise, niche tourism supporting Seeds of Hope is based on bundles of adaptation services that maintain landscape diversity. Trade-off among adaptation services were also revealed. For example, most stakeholders initially viewed P. paniculata grasslands as a problem due to poor biodiversity, fodder quality, soil and snow stabilization (Quétier et al., 2010), but subsequently recognized these grasslands provide adaptation benefit via drought-resilient fodder production, landscape connectivity, carbon storage

and water quality regulation. Knowledge of bundles of adaptation services revealed new opportunities: grazed terraces, which perform poorly for most ecosystem services and adaptation services, but have high transformative capacity and can provide shade for stock when colonized by trees and shrubs, thus supporting future adaptation. If mowing ceases on selected terraces in Seeds of Hope (WA2), the mosaic of mown and grazed terraces becomes an asset.

Fourth, adaptation pathways analysis reveals key path-dependencies, decision timeframes and related constraints (Brown et al., 2016; Brunner and Grêt-Regamey, 2016; Colloff et al., 2016a; Prober et al., 2017; Wise et al., 2014). We identifi early (WA2) and later (WA4) tipping points towards the undesired Ranching vision, where powerful incentives of short-term decisions (financial gains from intensive tourism and pasture allocation to transhumant herds) can be maladaptive in the long term. Timing and scale of land use and policy decisions and actions determines outcomes for SES and their ecosystem and adaptation services (Brunner and Grêt-Regamey, 2016; Prober et al., 2017). Path-dependent maladaptations were revealed, e.g. erosion on unmown terraces in Ranching. While strongly rejected by many stakeholders, Wild Mountains is plausible and could be adaptive given a series of extreme events and transformed social values that determine policies for agriculture, climate and nature protection (WA6).

Finally, the VRK perspective could be used to reframe decision contexts to create options that would not exist otherwise. Including or excluding various forms of values, rules and knowledge from decision making can shift context and outcomes (Gorddard et al., 2016). For example, resistance to change (rejection of new mowing equipment and manure management methods) could be overcome by including the VRK of younger farmers and activating novel options from system design approaches (Berthet et al., 2018). The VRK analysis revealed key leverage points for transformation (Abson et al., 2017) in a system where there are deep human-nature connections: institutional failure was experienced during the Chambon road crisis but adaptive actions and (informal) institutions emerged (R). An LTSER site, like the SES described here, meets requirements for knowledge co-production for

sustainability transformation: solution-oriented, transdisciplinary research with mutual learning, that incorporates values, norms and context into knowledge production.

5. Concluding remarks

At the regional scale, beginnings of pathways towards each of the four visions are already present. As a means to initiate transformation from "Seeds for a good Anthropocene" (Bennett et al., 2016) the TARA framework fosters learning and creation of new options, and adds to de-liberation and appropriation of scenarios to inform local decision-making and higher scales policy. By creating empowerment and recognizing local stewardship it has engaged local and regional stakeholders who now become actors of advanced transdisciplinary research, where detailed pathways will be co-designed (De Stefano et al., 2017; Fazey et al., 2016).

Acknowledgements

This work was funded by French Agence Nationale pour la Recherche BiodivERsA REGARDS (ANR-12-EBID-004-01), MtnPaths (ANR-16-CE93-0008-01), Labex Item (ANR-10-LABX-50-01) and Investissements d'Avenir CDP Trajectories (ANR-15-IDEX-02). This research is part of LTSER Zone Atelier Alpes. SL acknowledges support from the CSIRO Visiting Scientist Program. Ethics consent were obtained from participants for all interviews and workshops. We acknowledge the exceptional participation by inhabitants from Villar d'Arêne and La Grave and are indebted to Pierre Rizzardo and Sonia Paquet for facilitation initiation of this transdisciplinary research during the Chambon crisis. This paper is a contribution from the Transformative Adaptation Research Alliance (TARA, https://research.csiro.au/tara/); an international network of researchers and practitioners dedicated to the development and implementation of novel approaches to transformative adaptation to global change.

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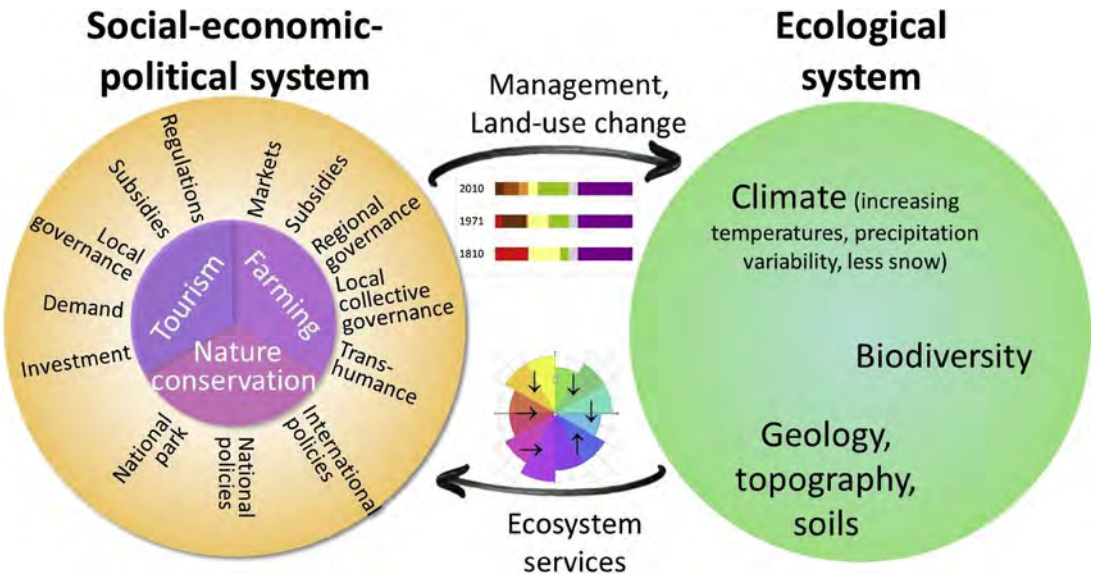

Fig. 1. Socio-ecosystem characteristics. Synthesis of the social system with its three main activities and their governance; biophysical system: main drivers and land cover dynamics since the 19th century, and landscape-level bundle (star plot) of most important ecosystem services since the 1970s (from Lavorel et al.,2017)

Table 1
Four visions for Lautaret. Key elements from interviews and scenarios for local population, agriculture and tourism activities and impacts on landscape and biodiversity.

Vision	Social / population	Agriculture	Tourism and infrastructure	Landscape	Nature / biodiversity
Seeds of Hope	Stable or increased population Socially diverse Quality of life rather than material motivation	Maintained livestock farming: local farmers and transhumant herds Diversifi of livestock production New vegetables, berries, aromatic & medicinal plants	Soft, diversifi (sport, resourcing, cultural), limited infrastructure. More summer Tourism Compact villages Maintained road system and enhanced e-connectivity	Maintenance of open landscape, terraces (not all) and mowing New crops on some terraces near villages Focused erosion and woody encroachment on terraces	Nature protection supported by locals Diverse fl
Local subsistence	Increased population, especially younger Subsistence motivation	Intensifi local livestock farming, incl. dairy production. Sown grasslands local consumption	Limited tourism Compact villages Limited maintenance of road	A predominantly agricultural landscape Restoration of terraces	No more nature protection institutions – national park no longer in action
Ranching	Decreasing population No local farmers Tourism workers	Gradual reduction and ultimate extinction of local livestock farming Cessation of mowing Grazing by external enterprises. Overgrazing on dry years	Development of mass winter and summer tourism and infrastructure. Urban sprawl Upgraded road system and e-Connectivity	Maintenance of open landscape at upper altitudes but marked woody encroachment Degeneration of terraces, and prevalent erosion	Decreased plant diversity (fl Increasing wolf populations
Wild mountains	Almost none	None Remaining small herds for subsistence, e.g. goats	Limited activities by motivated nature lovers Abandoned villages Decay of infrastructure	Marked woody encroachment and ultimate forest recolonization	Increased wildlife: ungulates, predators (wolf, lynx), raptors

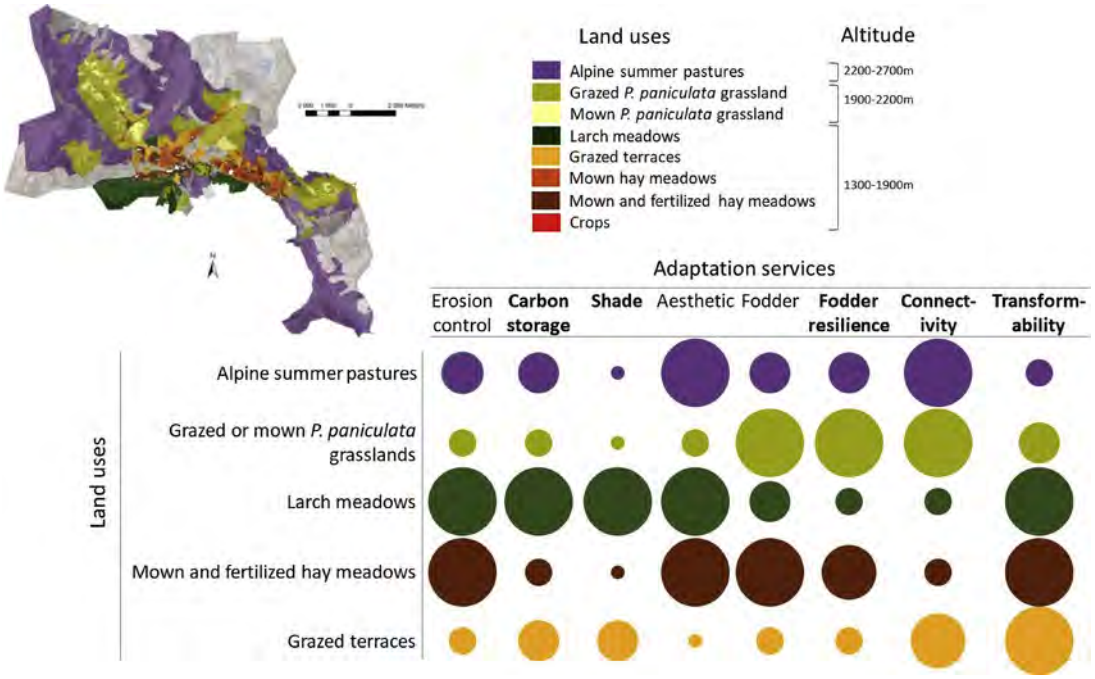

Fig. 2. Bundles of ecosystem and adaptation services for different grassland types. Adaptation services (in bold) include (i) ecological properties that support the persistence of current ecosystems and their services, (ii) latent ecosystem services (currently not or little used but of value for adaptation) and (iii) ecosystem transformative capacity that supports (iv) novel ES emerging from new biophysical and social contexts (Colloff et al., 2016). Land use types distribution and dynamics are detailed in Supplementary Fig. 1

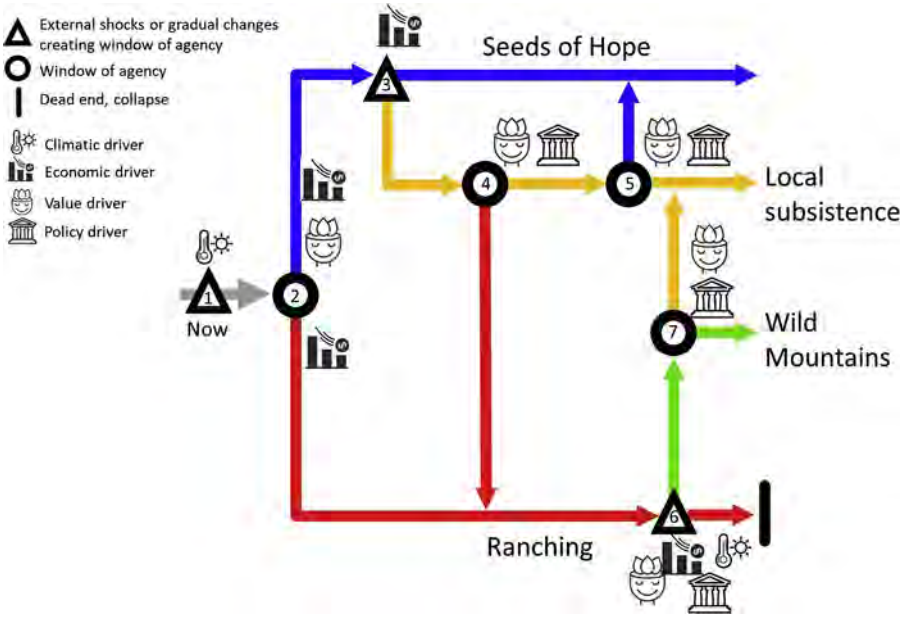

Fig. 3. Pathways and windows of agency towards the four visions. Each numbered window of agency is associated with specifi events, with respective symbols (legend inset). Arrows indicate pathways between windows of agency. Design inspired by Haasnoot et al., 2012

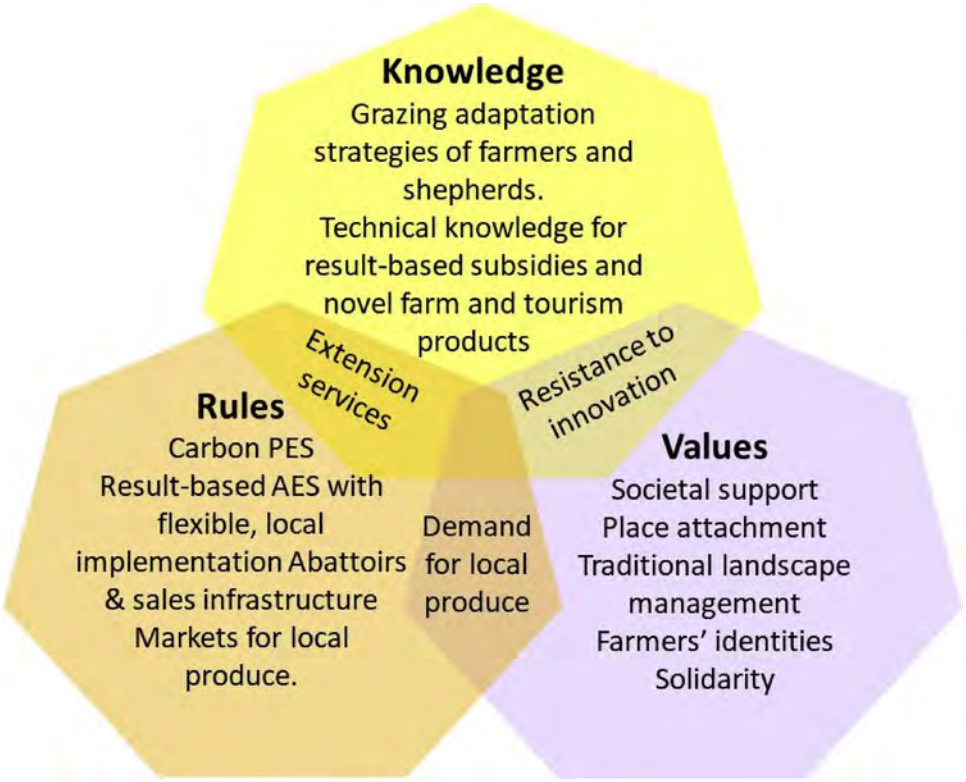

Fig. 4. Values-Rules-Knowledge constraints and enabling factors for the Seeds of Hope adaptation pathway