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EDITORIAL

Trajectories of socio-ecological change in mountains

Sandra Lavorel[1] · Sandrine Anquetin[2] · Nicolas Buclet[3]

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Introduction

Sustainable development is the biggest challenge faced by humanity. The UN Sustainable Development Goals largely promote human wellbeing through sustainable use of natural resources. Meeting the Sustainable Development Goals is impossible until the joint biodiversity and climate crises are resolved. Many solutions to these planetary issues are common and can be synergistic (Pörtner et al. 2021). Yet, this challenge is multi-faceted and complex because it links to the full recognition of the problem of providing for societal wellbeing while acknowledging some natural limits, some of which may have already been exceeded globally. This will only be possible if their common causes are addressed by transforming the dominant societal model of economy, governance, and societal values (Pörtner et al. 2021). Also, at regional (i.e. European Union) or national levels, such higher-order societal and political challenges need to be negotiated with more proximal and immediate issues, complicating the policy agenda and its translation to action.

Mountain social-environmental systems (SES) are iconic in Europe, and host major economic activities. In some alpine valleys, increased population is attracted to their natural resources and amenities. Mountain SES provide a disproportionate measure of critical ecosystem services (or nature's contributions to people — NCP) to people living both in and outside mountain regions, such as energy, water, food, protection from natural hazards, and multiple cultural benefits. These contributions depend largely on land use, itself shaped by long-established interactions of humans with nature in SES (Martín-López et al. 2019).

Because of the unprecedented rates and magnitude of environmental and societal changes including globalisation and climate change, mountain SES are regarded as highly vulnerable, with the risk of jeopardised NCP supply and therefore human wellbeing (Klein et al. 2019). Regarding the biophysical dimensions of global change, mountain regions world-wide and the Alps in particular are already experiencing faster temperature change than the global average, precipitation regimes are uncertain and unlikely to experience increased variability, and serious hazards are expected from natural risks (Pörtner et al. 2019). Regarding socio-economic change, the intensification and globalisation of international trade amplifies the high heterogeneity of land use within and across mountain regions (Levers et al. 2016). Depending on political and market conditions, a decline in the use of unfavourable agricultural areas (i.e. land abandonment and re-forestation) or increasing land use intensity in favourable areas is taking place, with potentially both negative and positive impacts on biodiversity and NCP, and resulting spatio-temporal trade-offs (Locatelli et al. 2017). Such changes necessarily feedback on mountain economies, with potential consequences for their future social and economic trajectories.

However, currently it is not clear to what extent mountain SES are vulnerable to ongoing environmental and societal changes, and whether they have developed a high resilience over their history of mutual adaptation and co-evolution between humans and ecosystems (Klein et al. 2019). If so, the limits of this resilience are unknown, and their prediction uncertain. This uncertainty pertains to the resilience and transformation mechanisms of the ecological and human sub-systems, and the robustness or vulnerability of the entire

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✉ Sandra Lavorel
sandra.lavorel@univ-grenoble-alpes.fr

Sandrine Anquetin
sandrine.anquetin@univ-grenoble-alpes.fr

Nicolas Buclet
nicolas.buclet@univ-grenoble-alpes.fr

[1] Laboratoire d'Ecologie Alpine, Université Grenoble Alpes, Université Savoie Mont-Blanc, CNRS, 38000 Grenoble, France

[2] Université Grenoble Alpes, IRD, CNRS, Grenoble-INP, IGE, 38000 Grenoble, France

[3] Université Grenoble Alpes, CNRS, Sciences Po Grenoble, PACTE, 38000 Grenoble, France

system coupled through land use decisions and NCP. Resolving this uncertainty is essential to guide coherent policy development, especially in the areas of land planning, agri-environment and rural development, biodiversity conservation, energy transition, or tourism, where sectoral policies with conflicting objectives must be integrated.

Given these challenges, a better understanding of processes of adaptation and co-evolution between mountain societies and their environment is essential. In addition, because adaptation, and especially transformative adaptation under highly uncertain climate change, is conditioned by decision contexts, such research cannot provide solutions to society unless it is designed and conducted directly with actors and decision-makers at different scales. In this novel, post-normal setting, scientists are challenged not only to embrace interdisciplinarity, which is required for complex social-environmental system research, but also to assume a new posture where scientists become knowledge brokers and actors of social change (Steger et al. 2021).

Papers presented for the Topical Collection are produced by the Trajectories cross-disciplinary project (https://trajectories.univ-grenoble-alpes.fr/) which aimed at improving knowledge on the interactions between human societies and their environment in Alpine regions. Trajectories' approach consisted in exploring temporal trajectories in order to anticipate changes and help territories adapt to climate and concomitant future challenges. Specifically, the overarching project goal was to support a dialogue among researchers and territorial actors with observations, models, and participatory assessments in order to imagine likely future trajectories. Specifically, Trajectories (1) developed innovative tools to bridge the gap between knowledge creation and end-user needs; (2) developed and applied models of social-ecological responses to global change; (3) reconstructed past social-environmental trajectories from direct observation, natural and social data synthesis, and modelling approaches; and (4) co-designed with local actors future pathways of global change adaptation. The twelve contributions to the Topical Collection are organised in three themes: (1) analysing past, coupled trajectories of climate, land change and natural risks; (2) resources for capabilities and mountain territorial dynamics; (3) nature-based pathways of climate change adaptation.

Past trajectories of climate, land change, and natural risks

Availability of data from contrasted disciplinary origins and covering a sufficiently long common period is a first main issue to address complex, human-climate-environment interactions. Due to the scarcity of in situ observations before 1900 anywhere in the world, and in particular in mountain regions where observations are still missing today for high elevation areas, the use of simulated climate variables is unavoidable even if their evaluation is challenging. Beaumet et al. (2021) built a high-quality dataset based on regional climate simulation at 7 km resolution, for the whole alpine region over the last century. They present modelled trends in simulated snow cover and temperature over the twentieth century, compared with reanalyses. These show contrasted seasonal trends for temperature and precipitation for low and high elevation regions. The large bias between the reanalyses and the simulations highlights the remaining uncertainties on climatic trends in high-mountain regions.

Two most iconic and noticeable consequences of anthropogenic climate change in mountains are the decrease of snow cover and the mass loss of glaciers. Snow cover duration has been consistently decreasing throughout the Alps, with sharper decreases at low elevations (Beaumet et al. 2021). This may affect the evolution of avalanche risk which is partly driven by spatio-temporal changes in snow and weather patterns, but not only. The evolution of risk (based on hazard and vulnerability) is directly linked to the co-evolution of its socio-economic, land cover, and climate drivers. Through an innovative combination of diachronic processing of old maps and photos, geohistorical analysis and various qualitative and quantitative modelling techniques Zgheib et al. (2022) show for the 1860–2017 period the importance of local dynamics including land cover change, especially afforestation, and of changes in exposure to avalanches mainly associated with social and economic developments.

By combining environment DNA records, ecology, and history, long-term trajectories are accessible to investigate the complex human-climate-interaction interactions. Using the long-term lake sediment archive for the whole Alpine region, Elleaume et al. (2022) and Giguet-Covex et al. (2023) demonstrate the value of an integrated social-ecological approach to improve our understanding of the structure and functions of mountain ecosystems. Elleaume et al. (2022) characterised the trajectory of an alpine socio-ecosystem over the last 500 years, while Giguet-Covex et al. (2023) analysed the history of agropastoral activities since 3600 BC in three alpine valleys. Giguet-Covex et al. (2023) show that pastoral activities first developed in high-altitude areas during the Mid-Late Bronze Age. Then, during the High and Late Middle Ages, all vegetation belts were used for pastoral activities, while crop diversification took place in the montane belt. Elleaume et al. (2022) further demonstrate how crop farming cessation since the beginning and especially the middle of the twentieth century has led to reforestation constituting a major social-ecological change with system-wide consequences as illustrated in the case of soil erosion.

Resources for capabilities and mountain territorial dynamics

Most resources exist because of interactions between human societies and ecological systems. Agricultural land is one of them, particularly scarce in mountains because of climate and topographic constraints. The history of mountain social-ecological systems is characterised by phases of extension and retraction of agricultural areas and forests (Elleaume et al. 2022; Giguet-Covex et al. 2023). Pressure exerted by agriculture leads to a trade-off between human activities and resource preservation. This is the main scope of the paper of Bertsch-Hoermann et al. (2021) which explores the potential of agroforestry for improving the trade-off between carbon sequestration and biomass provision in the Austrian Alpine context. Overall, while agroforestry allows significant carbon sequestration, at regional level, it implies reduced production. Nevertheless, agroforestry appears as a valuable option on alpine extensive pastures and meadows, enabling significant progress towards regional sustainability.

Resources are connected with capabilities, defined as the possibilities and opportunities of individuals to choose to achieve what they consider as a meaningful life (Sen 2000). Three papers link resources with individual as well as territorial capabilities (Bevione et al. 2022; Grosinger et al. 2021; Talandier & Donsimoni 2022). In the context of climate change and its consequences for mountain regions, these papers emphasise the importance of understanding how material as well as non-material resources are generated in a territory, illustrated for the French Maurienne valley. Collective intelligence and social interactions are highlighted as a way to increase capabilities of actors in the case of industrial activities (Talandier & Donsimoni 2022), and for dairy production (Grosinger et al. 2021). This typically non-material resource is critical for the co-production of NCP, such as fodder, local cattle breeds, or landscape aesthetics. Collective structures are crucial resources for the improvement of capabilities. They constitute territorial resources, i.e. resources specific to a territory, such as the Beaufort Cheese, which yields greater economic value compared to other cheeses not benefiting of such an organisation (Bevione et al. 2022). Bevione et al. (2022) and Grosinger et al. (2021) highlight how collective action reinforces multiple territorial capabilities reinforced. Ultimately, rural livelihoods appear as shaped by the interaction by the quality of available land resources with capabilities, allowing complementary social-ecological configurations across a territory and solidarity across more or less well-endowed areas (Grosinger et al. 2022).

Current and future vulnerability of territories is also considered. Bevione et al. (2022) identify the threats which might undermine some structural elements of dairy production in the Maurienne valley and their plausibility. The most credible threats are related to climate change and mostly water availability. Increased temperature, combined with probable decreased rainfall, is the main threat for agropastoralism, both directly with a reduction of fodder production, and indirectly with the negative impact of decreased snow falls on the ski industry, as farmers complete their revenues by working in skiing resorts. The central role of water availability as a critical resource shaping current threats and future adaptation pathways for agriculture and tourism is consistent with findings for the French Drôme Valley (Bergeret & Lavorel 2022). Climate change and decreasing rainfall might also challenge the present industry in Maurienne which relies on hydropower production. Lastly, Talandier and Donsimoni (2022) consider that the complete dependency of Maurienne on incoming and outgoing international flows of industry activities is an indicator of a weak territorial capability.

Together, this understanding of how activities are presently structured in the Alpine context, on which capabilities they rely on, is essential to support responses to conjectural (economical, institutional) and structural (climatic mostly) threats.

Nature-based pathways of climate change adaptation

Nature-based transformation is essential for sustainable futures (Díaz et al., 2019). Nature-based solutions (NbS), the actions to protect, sustainably manage, and restore ecosystems that simultaneously benefit people and nature, are critical for mitigating and adapting to climate change (Seddon et al. 2020). In mountains, passive forest restoration following historical changes in agriculture (Elleaume et al. 2022) and agroforestry (Bertsch-Hoermann et al. 2021) are among such options. Yet, beyond generic principles and a rapidly increasing number of place-based case studies (Chausson et al. 2020; Donatti et al. 2020; Dubo et al. 2023; Palomo et al. 2021), an evidence-based understanding of how people can activate nature's potential for transformation is missing. In addition, growing scholarship on the human dimensions of transformation has been largely disconnected from on the ground NbS initiatives (Palomo et al. 2021).

Nature-based adaptation cases combine bottom-up initiatives by individual land owners and managers or NGOs, and top-down projects by national institutions (national adaptation plans, nature protection, and primary industries organisations) or regional governments. Location of new NbS projects is rarely analysed strategically, nor has the distribution of existing projects been compared to needs in terms of current or projected

climate, potential impacts on current NCP, and the potential for ecosystems to address these risks through NCP supply. The novel analysis for 97 NbS projects across the Alpine Convention space gives the humbling conclusion that NbS are overall not located consistently with current supply, flow, or demand of most NCP, nor to climatic hazards (Dubo et al. 2023). This calls for structured knowledge systems (Tschanz et al. 2022) and institutional capacity (Panenko et al. 2021) for integrating local climate conditions, downscaled scenario projections (Jacob et al. 2020), and NCP maps (Schirpke et al. 2019) to underpin regional and macro-regional NbS strategies. The main implication of this analysis is that NbS implementation across the Alps is not driven by climatic hazards and NCP, but rather by social and human constraints including supporting regulations and institutions, finance, and societal support (UNEP 2022).

Bruley et al. (2021) and Bergeret and Lavorel (2022) address social and human barriers and levers for nature-based adaptation by analysing place-based cases of historical or anticipatory transformation across two contrasted regions, one high-altitude SES shaped by histories of agriculture and tourism and one watershed spanning from intensive agriculture and periurban plains to altitude grasslands and forests. These analyses are structured by the NCP co-production framework, which identifies natural and human-derived capital (or resources) involved in reconfiguring the flow of benefits from ecosystems to people's quality of life. In doing so, they identify required assets and decision contexts of interacting values, rules, and knowledge.

Participatory adaptation pathways often produce a majority of incremental options emphasising flexibility and low-risk strategies within existing economic systems, while establishing a basis for future potentially transformational actions (Cradock-Henry et al. 2020). Analyses in these two mountain SES show that, depending on the intensity of human capital reconfiguration and the type of NCP involved, adaptive responses range from resistance, to incremental, and to transformation of the governance system and socio-economic sectors. Although in mountains drivers of social-ecological change like public policies, markets and consumption patterns are mainly out of the control of local actors (Klein et al. 2019), mountain SES have a combination of favourable preconditions for transformative nature-based adaptation including high environmental and climate awareness (Wyborn et al. 2015) enhanced by recent extreme climate and other natural events, histories of innovation (Luthe & Wyss 2016), collective governance (Grosinger et al. 2021), and local leaders who promote participation for shaping major social and environmental changes (Luthe & Wyss 2016). At the same time, the social and governance structures and the infrastructure developed historically could generate path dependencies impacting future adaptation through locked land tenure and built assets, institutional structures and legacies, place attachment and local identities, conflict, and power relationships (Bergeret & Lavorel 2022; Bruley et al. 2021; Grosinger et al. 2021; Grosinger et al. 2022). Naturally slow ecological change, like reorganisation of plant communities or tree recolonisation, is also a major constraint (Bruley, Locatelli, Colloff, et al. 2021).

Conclusion

The twelve papers of the Topical Collection showcase several facets of mountain social-ecosystems as complex systems. They are shaped and evolve across time by interactions and feedbacks among multiple biophysical and societal drivers, multiple actors, and multiple resulting contributions of nature to people. Together the papers illustrate the benefits of quality, multidisciplinary, and co-located data to support their analysis. This nevertheless remains a major issue and calls for national, European, or international long-term observation strategies.

Mountain social-ecological dynamics involve systemic nonlinearities and thresholds. In particular, several of the papers emphasise the historical and current roles of high-impact climatic events and natural risks, which combined with specific societal changes have steered bifurcations in land use and economies. Such nonlinearities are inherently associated with systemic uncertainties on trajectories. Quantifying and communicating uncertainties is a cornerstone of environmental and social-ecological sciences. Future projections of climate change and biodiversity must be presented with uncertainties, associated with models, emission scenarios, and the internal variability of study system. Understanding how these different sources of uncertainty propagate from global to regional and local scales is fundamental for exploring future trajectories of mountain social-ecological systems.

Conversely, local dynamics stem from feedbacks between the social and biophysical subsystems through human agency, and especially land use decisions or institutional innovation for co-producing contributions of nature to people. These must be accounted for in future projections. Here, we clearly demonstrate the value for this of transdisciplinary processes with broad participation (Steger et al. 2021), and especially participatory pathway development (Bruley, Locatelli, Colloff, et al. 2021). Studies published in this Topical Collection are well underway towards co-producing future trajectories with mountain people, yet this will also require future transformation of our knowledge production and governance systems (Wyborn et al. 2019).

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