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Mountain research for sustainability: where are we and where to go?

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Abstract

Mountains have socio-economic and environmental importance for the entire world, and they are also one of the regions most threatened by global change. As mountains are systems in which the human and nature dimensions are tightly interconnected, studying them as social–ecological systems (SES) is increasingly common. To date, a variety of approaches and frameworks have been used to study mountain SES, making comparisons across mountain areas challenging. In this paper, we use Ostrom's SES framework to review the mountain SES peer-reviewed literature under a common scope, aiming at unraveling which frameworks, approaches, domains, sectors, and elements are studied by researchers. Among the 169 reviewed manuscripts, only 28% of them employed a framework to study their system, and custom-made frameworks were preferred over existing ones. Although most research articles were in the domain of environmental sciences, socio-economic attributes were included more often than ecological ones, and more than 30% did not combine social and ecological information. Moreover, albeit most manuscripts had an empirical approach, field data were seldomly used. Future works should focus on collecting social and ecological data at comparable scales, as well as on developing tools to effectively integrate both dimensions in mountain SES studies. Finally, we examine components of mountain socio-ecological systems commonly addressed in literature, highlighting important elements for overall and sector-specific sustainability. Regarding social aspects, understanding local inhabitants' diverse perspectives and socioeconomic context is crucial. In terms of ecological elements, describing climatic patterns and ecosystem history is key.

Keywords Social–ecological systems · Mountain sustainability · Global change · Trans-disciplinary research · Resource management

Introduction

Mountain areas are found on every continent. They occupy approximately 25% (Meybeck et al. 2001) to 39% (Viviroli et al. 2007) of the world's territory and are home to approximately 25% of the population globally (Meybeck et al. 2001). Mountains have social, economic, and environmental capital of significance for the entire world, since they harbor rich natural and sociocultural diversity, and provide essential ecosystem services to up to half of the world's population (FAO 2011, UNEP et al. 2020). Mountains also provide water for about 22% of the world's population (Immerzeel et al. 2019) and supply a substantial part of both natural and anthropogenic water demands (Viviroli et al. 2007; Immerzeel et al. 2010). Despite their geographical diversity, mountains also disproportionately contribute to the terrestrial biodiversity on Earth (Rahbek et al. 2019), hosting a diverse range of species, including many endemic, rare and threatened ones. Mountains partly or totally host approximately 30% of the total land area identified as terrestrial Key Biodiversity Areas (KBAs), and about 16.9% of the extent of the world's terrestrial protected areas network outside Antarctica is within mountains (Rodríguez-Rodríguez et al. 2011).

With rising global temperatures, mountainous environments are transforming rapidly. Nearly 60% of the mountainous area is under intense human pressure, predominantly at low elevations and mountain bases (Elsen et al. 2020). Mountain glaciers across much of the world are

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retreating (Dussaillant et al. 2019; Brun et al. 2017), impacting the water supply for up to 1.9 billion people (Immerzeel et al. 2019). These dramatic changes are expected to affect mountain hazards, such as the frequency and magnitude of flooding and landslide events (IPCC 2019). The steep terrain in combination with extreme climatic conditions, and in some regions seismic or volcanic activity, frequently triggers landslides, rock fall, debris flows, avalanches, glacier hazards and floods (Kargel et al. 2016, Kirschbaum et al. 2019). Since 2000, over 200,000 people have died in mountain regions (Immerzeel et al. 2019) because of disasters (Guha-Sapir et al. 2019). Numerous people living in mountains worldwide face multiple challenges in securing sustainable livelihoods. Poverty incidence in mountain areas is high, and close to 40% of the 835 million mountain people in developing countries are considered vulnerable to food insecurity (FAO 2015). Climate change, in combination with population growth, urbanization, and economic and infrastructural developments, is likely to exacerbate the impact of natural hazards and further increase the vulnerability of these regions (Huss et al. 2017; Mal 2018; Mann et al. 2017; Fischer and Knutti 2015; Haeberli et al. 2017). Climate change is also leading to widespread elevational shifts thought to increase species extinction risk in mountains (Elsen et al. 2020). Thus, all these stressors and processes threaten the sustainability of both the natural and human communities of mountain regions, and trans-disciplinary efforts among stakeholders, policy makers, and researchers of multiple disciplines are needed to address these challenges (Grumbine and Xu 2021, Klein 2019, Carey et al. 2017).

Research in mountain areas has been approached in different ways. On the one hand, projects may not consider or even mention that they have been carried out in mountain areas (e.g., Blumstein et al. 2005). Other projects consider that whichever the element under study, it is important to include the (mountain element) because of some of mountains specific characteristics (e.g., Martínez et al. 2012; López et al. 2009; Barrio et al. 2013). In this case, the authors may consider factors that are characteristic of mountains (e.g., slope or elevation in the case of natural communities—e.g., Richman et al. 2020—or isolation in the case of human populations—e.g., Urban 2020). Finally, other projects not only consider some mountain factors, but also acknowledge that mountain regions are social–ecological systems (SES), i.e., regions that share more characteristics within them than with the areas that surround them; mountains are systems in which the various dimensions (social, environmental, and economic) are tightly interconnected (all papers listed in Supplementary Material 2). Considering mountains as social–ecological systems has become relatively common during the last

years (Klein et al. 2019; Carey et al. 2017, see examples in Supplementary Material 2).

The SES concept is a way of integrating human–environmental interactions, connecting components of both through complex system feedback and dependencies (Berkes et al. 2003). Recent works have shown that such complex problems cannot be analyzed only with disciplinary approaches, but they must be dealt with in an integrative and trans-disciplinary way that considers the interaction between social—including the economic—and ecological systems (Newell et al. 2005; Folke 2006; Ostrom 2007, 2009). Berkes et al. (1998, 2003) stated that biophysical models and environmental research alone may not be enough to inform managers to take decisions to ensure the sustainability of a system. Thus, the development of a holistic approach to identify and mitigate environmental challenges, considering local and global, environmental and social contexts, is essential for advancing the understanding of how the various elements interact in a given territory. An SES approach accurately reflects the chaotic real world in which human and ecological systems reciprocally interact (Folke 2006; Alessa et al. 2015), and, at least theoretically, facilitates environmental management through the application of inter- and/or trans-disciplinary concepts.

Various approaches that include both the social and the ecological systems have already been developed and applied (Young et al. 2006; Binder 2007, 2013; Liu et al. 2007; Herrero-Jáuregui et al. 2018; Colding and Barthel 2019). Scholars use different frameworks, work at different scales, and apply different methodologies to study their social–ecological systems (Herrero-Jáuregui et al. 2018; Colding and Barthel 2019). A preliminary literature review by the authors showed that this seemed to be the case for studies on mountain social–ecological systems as well. Few works describing their mountain systems as SES had indeed used any framework to study them, either by applying an existing one (e.g., Al-Kalbani et al. 2016; Morán-Ordóñez et al. 2013) or by developing a new one (e.g., Capitani et al. 2019; Perez-León et al. 2020). Although this probably reflects the specificity of each case study, the lack of a common language and organization may hinder the comparison between different works (Poteete and Ostrom 2008; Ostrom 2007, 2009).

Among the different frameworks developed by researchers, one of the most extensively used ones is Ostrom's multi-tier social–ecological systems framework (sensu Colding and Barthel 2019). Ostrom's social–ecological systems framework (from now on, Ostrom's SES framework) proposed by Dr. Elinor Ostrom (2007, 2009) and then complemented by others (Epstein et al. 2013; McGinnis and Ostrom 2014; Vogt et al. 2015) is arguably the most comprehensive conceptual framework for analyzing elements, interactions, and outcomes in social–ecological systems (Partelow 2018). It provides a common language for organizing the many variables relevant

in the analysis of SES into a multi-tier hierarchy that can be unfolded when needed. Ostrom's SES framework is now viewed both as a theoretical framework to advance collective action theory, and as a general tool to diagnose the sustainability of social–ecological systems (Partelow 2018). Ostrom's SES framework has been used to characterize systems due to its comprehensive and flexible list of potential elements, its ability to work at multiple scales, and its capacity to include both qualitative and quantitative data (del Mar and Ramos 2015). These characteristics also make Ostrom's SES framework a useful tool to frame the mountain SES literature under a common scope.

In this work, we aim at finding patterns and trends in mountain SES studies. We want to unravel which, if any, SES framework is used, which scale and approach (empiric or conceptual) is taken, which domains and sectors do researchers study, and which SES elements researchers include in their works. To classify the SES elements included in the works of researchers using different frameworks and approaches, we use the systematic and comprehensive classification of SES elements provided by Dr. Elinor Ostrom (Ostrom et al. 2007, 2009). Integrating the literature under Ostrom's SES framework enables us to see patterns in the inclusion (and omission) of SES elements in mountain SES studies, letting us see what researchers deem as most important, as well as to uncover potential gaps. We specifically aim at answering these questions: (i) is there a bias in the inclusion of socio-economic versus ecological attributes? (ii) Which elements do researchers consider most important when studying mountains under a social–ecological system's perspective? (iii) Which SES elements are frequently studied together? and (iv) are there asymmetries in the literature, e.g., are there any specific SES elements that are underrepresented?

Our results will be helpful to shed light onto how researchers have approached the study of mountain systems under an SES perspective so far, regarding their frameworks or approaches, scales, domains, sectors, and studied elements. Moreover, by bringing together the work of the researchers investigating mountain social–ecological systems across scales, frameworks, and approaches, we provide some guidance as to which SES elements to include in future studies. We identify key SES-elements that projects addressing the sustainable management of mountain resources include, as well as relevant elements per sectors. Finally, by exposing asymmetries in the literature, we identify potential gaps of knowledge and give recommendations for future lines of research.

Methods

A bibliographic search was carried out in the ISI Web of Science database using the following syntax: (mountain* AND (social–ecological OR socio–ecological) AND system*),

obtaining a total of 317 references. Search was restricted to documents published from 2000 onwards to ensure that the SES concept used in these papers was as close as possible to the recent understanding of social–ecological systems. Papers mentioned in the reference list of the analyzed documents were eventually added to our database if they referred to mountains as social–ecological systems in their title or texts. The following data were initially collected for each document: authors, region, framework used (if any) and sector under study. We then investigated which elements were addressed in each study. To classify these elements, we followed the taxonomy provided by Dr. Elinor Ostrom et al. (2007, 2009), structured into tiers of nested and related concepts and variables. The first tiers include the Resource System (RS), Resource Units (RU), Governance System (GS), Actors (A), Social, Economic and Political Settings (S), Interactions (I), External Ecosystems (ECO), and Outcomes (O). Second-tier variables are nested within each first-tier variable. We added Epstein et al. (2013) Ecological Rules (ER) to the list of first tiers. First-tier and, when it was clear, second-tier attributes (Table A1 and Fig. A1, Supplementary Material 1) were assigned to all SES elements included in the studies. We decided not to include either of the Ostrom's SES framework Interactions or the Outcomes because they represent another category of attributes, are part of the description of the SES itself, and include elements that have already been included in the RS, RU, A, GS, CLIM, ECO and/or the ER.

As expected, papers that did not use Ostrom's SES framework (SESF) did not use its vocabulary or taxonomy. In this case, we tried to match as best as possible each paper's vocabulary to Ostrom's attributes. For example, when papers mentioned (…We conducted a series of interviews–questionnaires with the local population, which enabled us to define their profile and to evaluate their perception of the landscape…) (Rescia et al. 2008), the attribute A7 (Knowledge of SES/Mental models) was assigned to this paper. We were able to assign Ostrom attributes to all study objects. Some researchers have raised awareness about the ambiguity in the interpretation of the SESF attributes (del Mar and Ramos 2015; Partelow 2018). In our case, the whole process was independently carried out by the two authors and agreed when assignments differed. Papers were rejected because of one or more of the following reasons: the study was not carried out in mountains; papers were purely theoretical; and/or papers were not based on a sector (RS or RU), accepting at most (Ecosystem services) as a sector (RS1). Finally, following Herrero-Jáuregui et al. (2018) we also noted the approach (Empirical or Conceptual), the biophysical scale (Field, Landscape, or Remote) and the domain (Environmental, Social, and Agricultural and Biological Sciences).

With this information for each reviewed study, we investigated: countries/regions covered by the studies; number of

papers using or not a framework/approach; number of papers using each framework/approach (including custom frameworks as a category); and number of papers per approach, scale, domain, and sector. Then, following Ostrom's classification, we investigated the number of attributes addressed per paper; number of attributes addressed per framework; number of papers addressing only socio-ecological attributes (GS, A, S), only ecological attributes (RS, RU, ECO, ER), both socio-ecological and environmental, globally and separating by works using a framework and not using one; number and type of attributes per sector; number of papers addressing each attribute; and relationships between attributes.

We created a list of the attributes that were not addressed in any of the analyzed papers. To investigate which elements are frequently studied together, we looked at the relationship between attributes. We built a matrix of interactions in which the cells included the number of times that each combination of attributes was found in the revised manuscripts. Several interaction networks were built: one in which we included those interactions that had been addressed in 10 or more papers, and individual networks centered on these most linked attributes. For this, we used the ggnet2 (Butts 2020a), network (Butts 2020a), and sna (Butts 2020b) R packages.

Results

Our final database included a total of 169 papers (Supplementary Material 2) from 42 different countries and other trans-national regions (Supplementary Material 3, Fig. A.9). Only 28% of them (47 papers) used one or more existing frameworks, whereas the rest mentioned SES in the text, but did not mention using any existing working framework. Among the ones that used existing approaches, sixteen different ones were mentioned, including custom-made as a category, which were the most used ones (31.9%), followed by Ostrom's SES framework and the Social–Ecological Resilience frameworks (Fig. 1; Supplementary Material 3, Table A.1).

Approach and scales

Most of the reviewed references had an empirical (67%) approach rather than conceptual (33%), and also most of them were taking a biophysical scale at the landscape level (80%), followed by field (14%) and remote (i.e., using remote sensing data, 6%) scale levels.

Domains and sectors

Domains. In total, 53% of the papers were classified in the environmental domain, 29% in the social domain, and 19% in the agriculture and biological domain (including pastoralism).

Sectors (Ostrom's SES framework Resource Systems and Resource Units) and attributes per sector. Analyzed papers addressed the various sectors with percentages that range between 8 and 17%. Most studied sectors were (Biodiversity), (Ecosystem Services), and (Water), (Fig. 2, top left). All elements (ECO, S, ER, RS, RU, GS, and A) appear in all these sectors, with a clear dominance of Actors (A) and Governance Systems (GS), and the lowest presence of Social, Economic and Political Settings (S) (Fig. 3).

(Biodiversity) was the most linked RS/RU to other attributes (25), whereas (Forest) (15) and (Agriculture) (13) were the least ones. Works focusing on (Biodiversity) mostly included the population mental frameworks (A7), climatic patterns (ECO1), equilibrium properties (RS6), and rule-making organizations (GS5) (Supplementary Material 3, Figure A.1).

When addressing (Water) (Supplementary Material 3, Fig. A.2) and (Ecosystem Services) (Supplementary Material 3, Fig. A.3), prioritized attributes were the population mental frameworks (A7), climatic patterns (ECO1), equilibrium properties (RS6), and rule-making organizations (GS5). In the case of (Ecosystem Services), population (GS3) was also among the most addressed attributes.

(Livestock) was mostly related to climate (ECO1), the population mental frameworks (A7), living population (GS3), equilibrium properties (RS6), and, to a lower extent, economic value (RU4) (Supplementary Material 3, Fig. A.4).

Finally, (Agriculture) (Supplementary Material 3, Fig. A.5), (Landscape) (Supplementary Material 3, Fig. A.6) and (Forest) (Supplementary Material 3, Fig. A.7) included the population mental frameworks (A7); (Landscape) and (Agriculture) included equilibrium properties (RS6), and climatic patterns (ECO1), the latest also included in (Forest); and (Agriculture) and (Forest) included rule-making organizations (GS5) and population (GS3); finally, (Forest) was the only one including ecosystem history (RS10).

SES elements addressed: Ostrom's attributes

Number of attributes per paper. The number of attributes addressed in single papers ranged between only 1 and a maximum of 14, with an average value of 3.9 attributes per paper, and without notable differences among sectors (Supplementary Material 3, Fig. A.8) and no evidence that the more papers addressing a sector, the more attributes when pooling by sector. The average number of attributes was higher in studies using a framework (4.8 attributes per study) than in studies not using one (3.4 attributes per study) (Supplementary material 3, Table A.1). Among the frameworks used in at least more than one study, the one that included
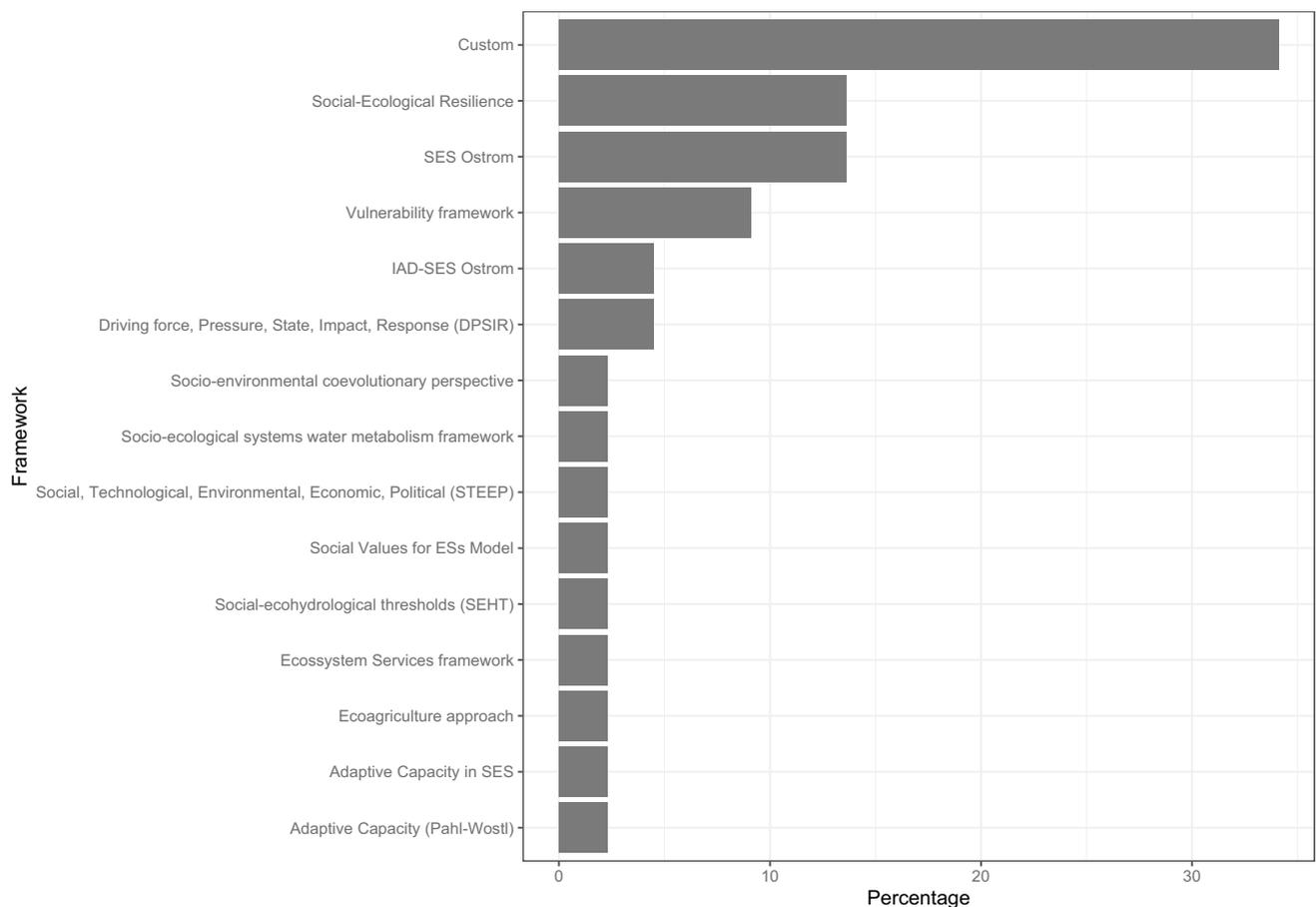
Fig. 1 Percentage of approaches (including frameworks) used by scholars in the reviewed works ($n = 169$). For details, see Table A.1 in the Supplementary Material. References in the main document: Ostrom SES (Ostrom 2007), Vulnerability framework (Adger 2006); References in the supplementary material: Adaptive capacity (Pahl-Wostl) (Wallrapp et al. 2019), Adaptive capacity in SES (Young and Kettenring 2020), DPSIR (Yu et al. 2021), Ecoagriculture approach (Tanguay and Bernard 2020), Ecosystem services framework (Moran-Ordoñez et al. 2013), IAD–SES (Graefe et al. 2019), SES water metabolism framework (Cabello et al. 2015), Socio environmental coevolutionary perspective (Pérez Leon et al. 2020), Social Values for EEs Model (Zhang et al. 2019), STEEP (Everard et al. 2018), Social Ecological Resilience (Daugstad 2019)

more attributes per study was Ostrom's SES framework (8 attributes per study), followed by Social–Ecological Resilience (5 attributes per study) and Vulnerability (4.2 attributes per study) frameworks (Supplementary Material 3, Table A.1). 65% of the works included both social and ecological elements together in their studies (110), followed by works addressing socioeconomic elements exclusively (47, 27.8%), while studies addressing only ecological variables were a clear minority (12, 7.1%) (Supplementary material 3, Table A.2). Works employing a framework (47, 27.8%) combined ecological and socioeconomic attributes slightly more often (37, 79%), and rarely employed only socioeconomic data or ecological data (8 papers, 17%, and 2 papers, 4.3%, respectively). Works not using a framework (122, 72.2%) used only socioeconomic data in 32% of the cases (39 papers), only ecological data in 8.2% (10 papers), and both in 59.8%. (Supplementary material 3, Table A.2).
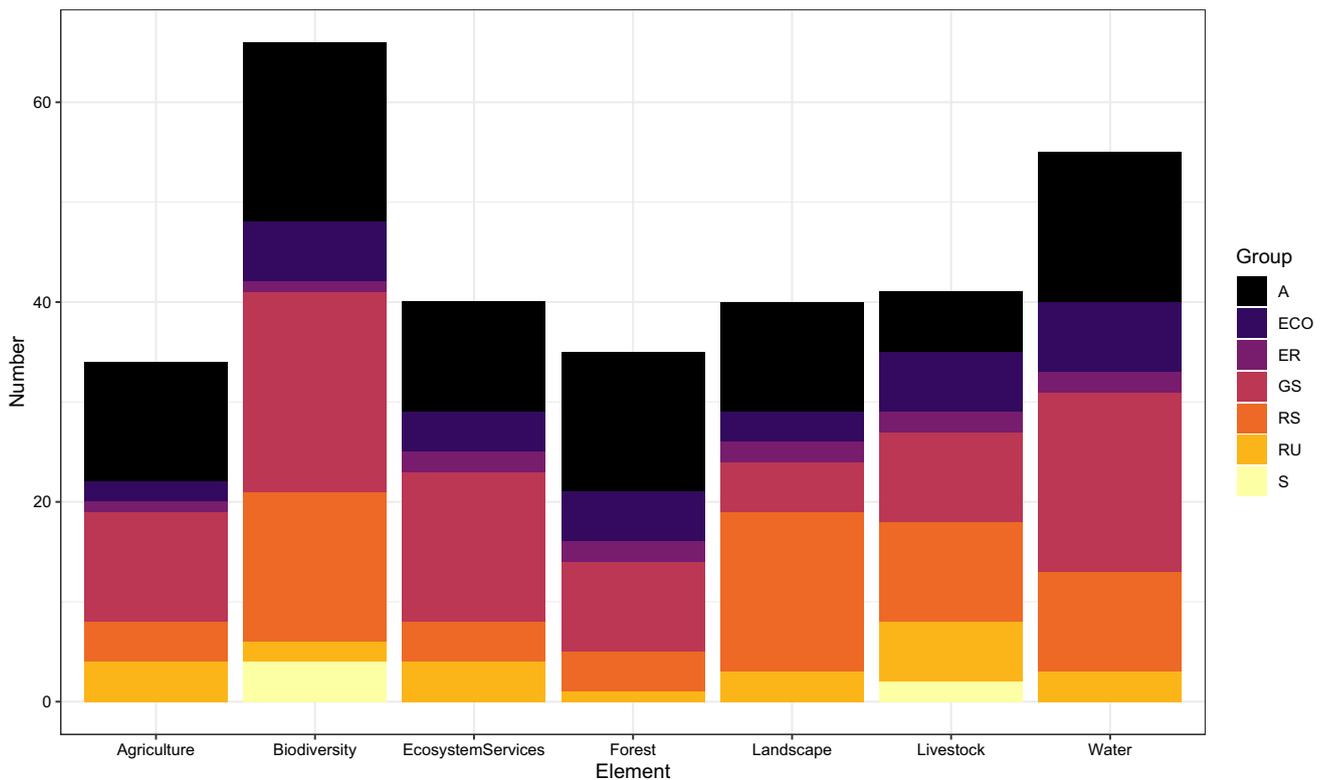
Ecological drivers attributes

Ecological drivers were included in 26% of the analyzed works (44 out of the 169 papers). Out of the papers addressing ecological drivers ECO1 (Climatic patterns) was used in most cases (93.3%), whereas the presence of ECO2 and ECO3 was minimal (4.4% and 0.6%, respectively, Fig. 2).

Social economic drivers attributes

Global social/economic drivers were included in 17.2% of the works (29 papers). Within them, nearly half of them addressed S1 (Economic development) (17 papers, 47.2%). The rest addressed S5 (Markets) (10 papers, 27.8%), and S2 (Demographic trends) (9 papers, 25%) (Fig. 2).
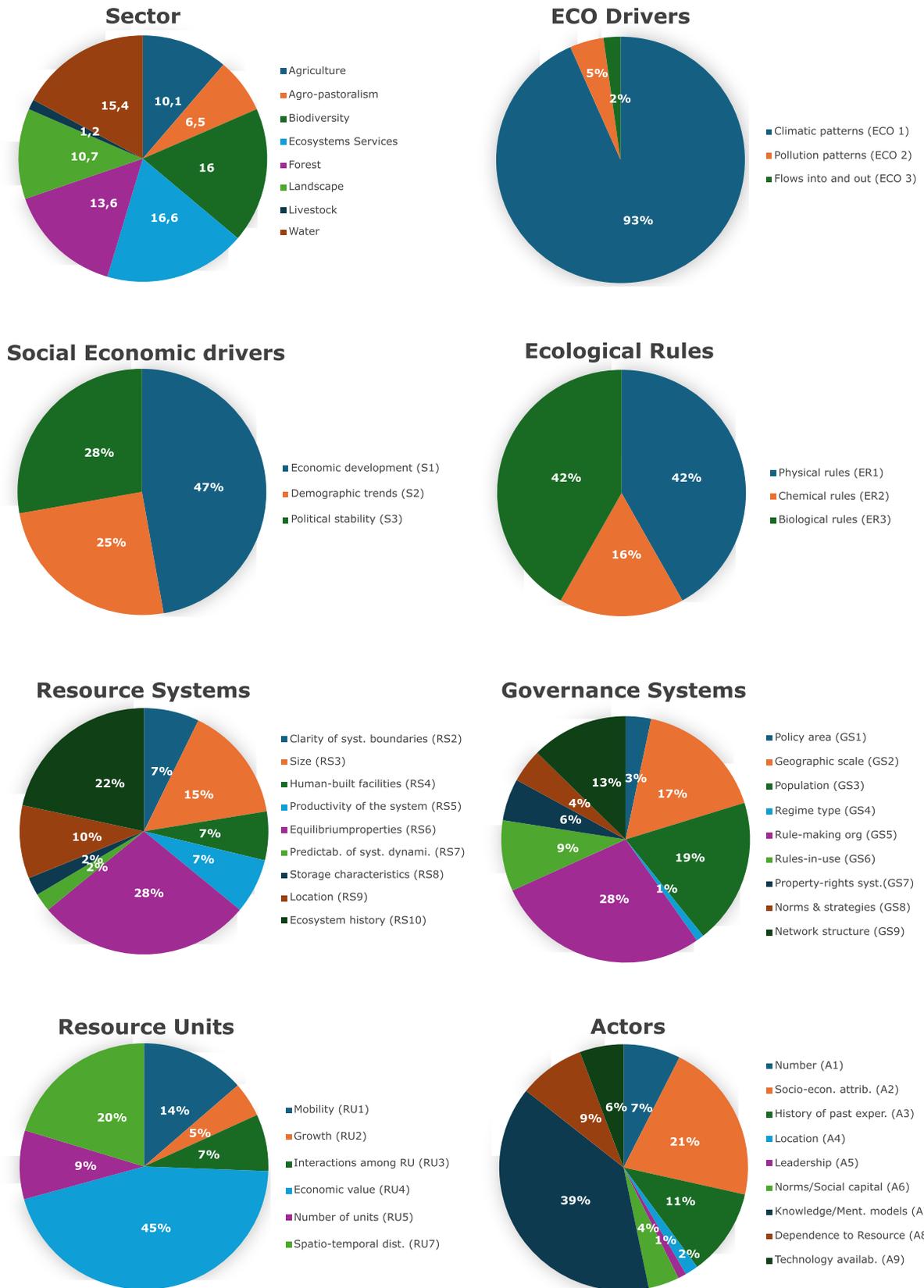
Fig. 2 Percentage of papers that addressed each sector, and the attributes of the ecological drivers, the social, economic and political settings, the ecological rules, the resource units and systems, actors, and governance systems (see Supplementary Material 1 for the code descriptions)

Fig. 3 Number of SES attributes addressed in the reviewed manuscripts when addressing each sector (Element) (*N* = 169) (*A*: actors, *ECO*: related ecosystems, *ER*: ecological rules, *GS*: governance system, *RS*: resource system, *RU*: resource unit, *S*: socio-economic and political drivers)

Ecological rules attributes

The attributes of the Ecological Rules were included in 33 papers (19.5%). 41.9% of these papers included ER1 (Physical rules) and 41.9% included ER3 (Biological rules) (Fig. 2). Physical rules were mostly related to erosion and or run-off events, and biological rules were most related to livestock or pest management. The least addressed ER was ER2 (Chemical rules), addressed only in 16.3% of the works.

Resource system attributes

RS attributes were included in 53.3% of the analyzed references. Among them, RS6 (Equilibrium properties) was the most included (28%), indicating that many works refer to any of the disturbance attributes that may affect the RS under study (frequency of the disturbances, intensity, magnitude, etc.) (Fig. 2). This is reinforced by the fact that RS10 (Ecosystem history) was the second most used RS attribute (21.6% of the cases); RS10 was assigned to studies that included land use change, natural disaster history, and or human use and disturbance history. With lower percentages, studies included RS3 (Size of the resource system, 15.2%), RS9 (Location, 9.6%), RS5 (Productivity of the system,

7.2%) and RS2 (Clarity of system boundaries, 7.2%). The least addressed RS attributes were RS7 (Predictability of the system dynamics) and RS8 (Storage characteristics).

Resource units attributes

Resource Units and their attributes are not much referred to in our review. Only 38 (22.4%) mention RU attributes, probably indicating that, even though RS are formed by RU, researchers prioritized working at the RS level. Nearly half of them (46.5%) include RU4 (Economic value); RU7 (Spatial or Temporal distribution) appeared in 20.9% of the works, and RU1 (RU Mobility) was considered in 14% of the works (Fig. 2).

Governance system attributes

Governance System attributes were considered in more than half (58.6%) of the 169 analyzed papers. Among them, GS5 (Rule-making organizations) was included in 27.9% of the cases. GS5 includes all works in which community-based organizations, public and private sectors, and/or NGOs participate to manage the RS/RU (Fig. 2). Population (GS3) was the second most addressed attribute (19.1%), close to

the geographical scale of the governance system (GS2). GS9 (Network structure) was also included in 12.6% of the cases, showing a relative importance of how the various governance institutions were related and how hierarchies among them could play a role.

Actor attributes

These were the most addressed attributes, as more than half of the reviewed works (54.7%) included one or more Actor attributes. Most of them (38.9%) gave much importance to the perceptions that actors had on the RS or the RU and how they could be related to their environment sensu lato (A7, Knowledge of SES/Mental models) (Fig. 2). In most cases, this was carried out through in-person or virtual surveys. 11.4% of them referred to A3 (History of past experiences), which included works where, for example, land abandonment by the actors was considered. Socio-economic attributes (A2) were also present in many (21.1%) works.

Non-addressed attributes

Non-addressed attributes were RU6 (Distinctive characteristics), GS10 (Historical continuity), and several socioeconomic drivers: S3 (Political stability), S4 (Other governance systems), S6 (Media organizations), and S7 (Technology).

Relationships between attributes

The global representation of links between the SES elements shows a complex net of interactions—understood as elements or attributes studied together. Among the addressed attributes, thirteen were the ones that appeared linked more

frequently (i.e., in 10 or more papers) than the rest: A2, A7, ECO1, GS5, GS9, RS6 and RS10 (Fig. 4). Two of them (GS9 and RS10) are linked with only one other attribute, and the rest of them present links with 2 (RS6 andA2), 3 (GS5 and ECO1), or 4 (A7) attributes.

The most frequently linked Resource Systems attributes (RS6—equilibrium properties-, and RS10—ecosystem history) preferentially included ECO1 (Climatic patterns) and A7 (Knowledge of SES/mental models), respectively. GS5 (rule-making organizations) was also preferentially linked with A7, whereas GS9 (network structure) was most of the times considered with GS5. There are two Actor attributes in the list of the most linked ones, A7 (Knowledge of SES/ mental models) and A2 (Socio-economic attributes), both linked most of the times and also ECO1 (Climatic patterns) and RS10 (Ecosystem history) (Supplementary Material 3, Fig. A.10).

Discussion

Frameworks and approaches used

Our results show that scholars studying mountain social–ecological systems usually do not employ a framework to do so. Among those ones that do, varying frameworks were identified, and custom frameworks were the more commonly used. This indicates that there are many approaches to studying mountain SES. Many researchers highlighted the specificity and uniqueness of their case studies, which may explain why they could be reluctant to employ one-for-all frameworks and prefer custom approaches. In several cases, these custom frameworks were derived from well-known

Fig. 4 Links between the pairs of attributes that are mostly addressed together in the same manuscript (*A*: actors, *ECO*: related ecosystems, *GS*: governance system, *RS*: resource system, *RU*: resource unit)
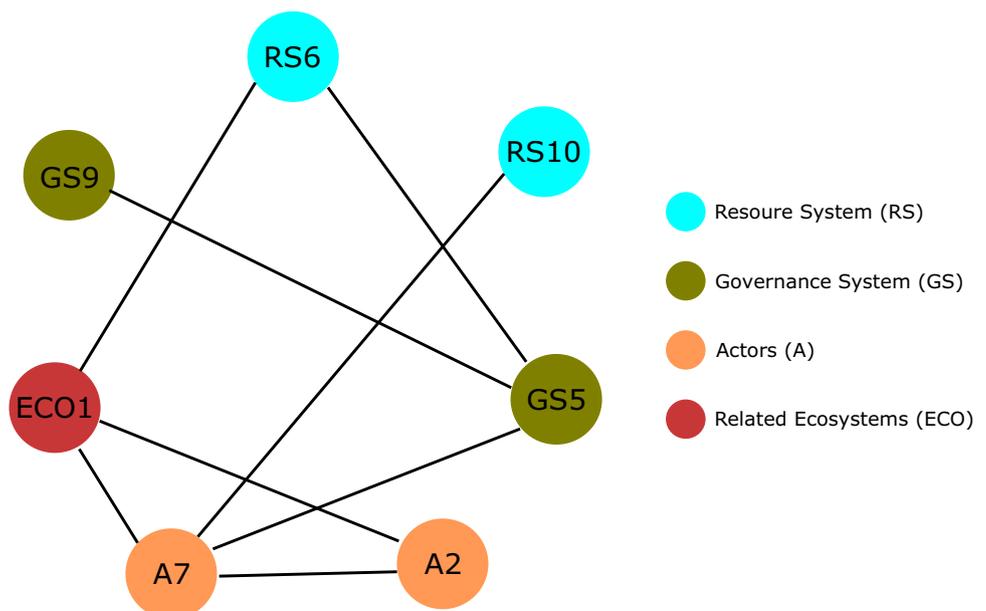
frameworks, such as Vulnerability (Adger 2006) or Resilience frameworks (Folke 2006). For instance, Kohler et al. (2017) used a conceptual approach stemming from the Resilience framework to study a livestock system. Other scholars, such as McCord and collaborators (2017), combined two frameworks to analyze their social–ecological system: the Institutional Analysis and Development framework (Kiser & Ostrom 1982) and Ostrom's SES framework (Ostrom 2007, 2009).

Often, we were able to identify more Ostrom's SES framework attributes in works employing a framework than in works that did not use one. This is probably because frameworks offer a systematic approach and a specific terminology to analyze the system (Colding and Barthel 2019; Ostrom 2007, 2009), which facilitated the classification of the elements under study. In any case, each framework has different setups, priorities, and goals (Herrero-Jáuregui et al. 2018; Colding and Barthel 2019), and combining them can be useful to take advantage of the strengths of each approach. For instance, Orchard et al. (2020) employed a custom framework which combined social vulnerability, natural hazard mitigation, and social–ecological resilience approaches to study sustainable development goals (SDGs) (Eakin et al. 2009; Suckall et al. 2018). Since each approach contributes differently to SDGs, their combination allowed them to understand the synergies and trade-offs between SDGs. Similarly, Brymer et al. (2016) built a comprehensive custom framework that combined ecosystem services framework (de Groot et al. 2002) with the social processes (Vanclay 2002) to study landscape changes. On the one hand, the ecosystem services framework allowed them to have a systematic approach to classify ecosystem functions, goods, and services. On the other hand, the social processes helped bring governance, economics, and leadership into the analysis. Thus, rather than being understood as fixed and unchangeable procedures, frameworks can evolve and become very useful when combined with each other to exploit their synergies.

The integration of the social and the ecological dimensions

Despite the holistic perspective of an SES approach, some of the reviewed works did not combine ecological and socioeconomic information. Moreover, there seemed to be a bias towards the inclusion of socio-economic elements over ecological ones. This aligns with the findings of other studies not focused on mountains (Refulio-Coronado 2021; Herrero-Jáuregui et al. 2018). SES approaches were conceived to integrate social–ecological interactions into the same analysis (Newell et al. 2005; Folke 2006; Ostrom 2007, 2009). Thus, not combining ecological and socioeconomic

information seems contradictory, an issue which has been raised before (Rissman and Gillon 2017).

In a review that was not mountain-focused, Herrero-Jáuregui et al. (2018) found that the great majority of the analyzed SES studies corresponded to research articles in the domain of environmental sciences (60%), followed by social sciences (25%) and agriculture and biological sciences (15%). They found that despite this focus on environmental sciences, studies tended to include more socio-economic variables than ecological ones. We found very similar results regarding the domains and the inclusion of social–ecological variables studied in mountain regions. Herrero-Jáuregui et al. (2018) state that this suggests a greater research motivation of natural scientists to study SES, but also notice that there is an implicit risk of researchers with insufficient background in the social sciences simplifying the social dynamics of SES by incorporating just a few socioeconomic variables. Moreover, Rissman and Gillon (2017) showed that management recommendations were twice as likely to be addressed in studies incorporating both ecological and socio-economic variables. Scholars working in mountain systems seem to be aware of the importance of combining socioeconomic and ecological information, since most of the reviewed works did so. Of those that did not, the vast majority used only socioeconomic variables. Greater efforts need to be made to include biophysical variables together with socio-economic ones in mountain SES studies (Epstein et al. 2013; Rissman and Gillon 2017). Scholars of both social and environmental sciences must find the ways to connect and share their knowledge (Martin et al. 2012). This will help the development of the sustainability science, not only in mountains, but also for other regions (Folke et al. 2016; Herrero-Jáuregui et al. 2018).

The challenges of accessing adequate data to perform trans-disciplinary SES approaches probably helps to explain why some studies did not include more variables or combined both socioeconomic and ecological data (Herrero-Jáuregui et al. 2018). Most of the reviewed works employed an empirical approach. However, most of these empirical approaches are based on interviews and surveys, and they were seldomly combined with environmental field data. These data are difficult to combine due to the different temporal and spatial scales at which environmental and social scientists work, and finding appropriate methodologies to integrate them can also prove challenging (Herrero-Jáuregui et al. 2018, Graymore et al. 2008, Firscher et al. 2015, Kramer et al. 2017). For example, population dynamics may only be available for large territorial scales (national or regional) and at annual resolution. Conversely, field data are normally collected for a few years, at large territorial scales, and are usually taken at higher-than-annual temporal scales.

Thus, there seems to be a gap between theoretical SES conceptualization and the availability of empirical data and

methodologies to effectively enable the integration of socio-economic and ecological dimensions (Herrero-Jáuregui et al. 2018). New statistical tools such as Structural Equation Modelling (Filbee-Dexter et al. 2018), complex systems analyses (Mao et al. 2021), and neural networks and machine learning (Frey 2020) may help move one step forward from the pure description of a system, to enable the integration of social–ecological data to find which may be the consequences of a given action to the whole territory, at various dimensions and spatiotemporal scales. Similarly, the use of satellite data may solve some of the problems related to obtaining data, but matching environmental and social data may still be very challenging at the micro-scale in many systems. We also encourage a larger use of citizen science methodologies to obtain field data, both in the environmental and social domains (Danielsen et al. 2014; Aceves-Bueno et al. 2015). Citizen science projects reduce the cost of obtaining such information and have the potential to enlarge the territorial and spatial resolution of environmental data as well as collecting social data (Crain et al. 2014; Ballard et al. 2017), leading to a likely future (community science) approach (sensu Charles et al. 2020).

Most addressed elements

Despite the above-mentioned limitations, our results show that most studies include both social and ecological elements and that scholars make an effort to establish links between them. The most linked attributes show the complexity and reality of mountains as SES, and what researchers prioritize when studying their systems. Ostrom's SES framework was initially created as a tool for a sustainable management of resources, that could consider the social and economic dimensions of the target resource (McGinnis and Ostrom 2014; Partelow 2018). In the current frame of climate change highly affecting mountain regions (Huss et al. 2017; Mal 2018; Mann et al. 2017; Fischer and Knutti 2015; Haeberli et al. 2017), this is still more urgent and necessary. Using Ostrom's SES framework to structure the mountain SES literature provided insights into how researchers tackled this challenge to date.

The most connected attributes include socioeconomic elements related to the governance that may affect management at various scales, the different view and knowledge the local residents have on the exploitation of the environment, and the socioeconomic context of the local residents. As for ecological elements, they include equilibrium properties (including natural disasters), and two of the most important current drivers affecting natural systems' sustainability: the ecosystem history (analogue to land use change), and the climatic patterns (i.e., climate change). These attributes appeared repeatedly linked in studies working with different frameworks, scales, and approaches. This points at

their importance for the sustainability of mountain regions regardless of the methodology used.

Attributes per sectors

The most addressed sector was ecosystem services, and the next included some of the most threatened systems in mountain regions: biodiversity, water, forests and livestock (Stritith et al. 2020; Mengist et al. 2020; Yu et al. 2021). Two attributes were explored very often in all sectors: the mental models of the population and the climatic patterns. This indicates most scholars focus on the effects of climate change and the opinions of the local population on how the system should be managed, regardless of the sector from which they approach the study of their SES.

Certain attributes appeared more often when looking at specific sectors. Livestock and Agriculture are the sectors most closely linked to markets. Thus, it is in these sectors in which the economic value of the resource appears more often, as well as the socioeconomic situation of the actors. The different rule-making organizations were often considered in biodiversity, water, and agriculture sectors, indicating the complexity of managing these systems and the interplay of governance institutions involved. As for the Forest sector, the geographical scale of the governance system was often considered. This probably reflects the complexity of managing forest ecosystems from different, often conflicting institutions operating at local, regional, and national scales. Mountains provide many ecosystem services vital to people living in and outside them (EEA 2016). Ecosystem services addressed in our database include wood-based energy (Jensen-Ryan et al. 2019) and carbon sequestration (Ma and Coppock 2012), for example. Not surprisingly, the most addressed attribute in this sector together with the mental models and climate change is the socioeconomic situation of the region's inhabitants. This is because many studies focused on how the local residents envision the development of mountain regions under the threat of climate change, and how their livelihoods and social structure may be affected by the adaptation options.

Water is among the most important mountain ecosystem services, and it will play a very important role in the management of mountain resources in the future (Viviroli et al. 2011). Lower water availability due to climate change may lead to conflicts for water use, not only in the mountains but also in the lowlands, which are the main users of water (Viviroli et al. 2011; Fuller and Harhay 2010). Again, the most addressed attributes include climatic patterns, governance institutions, and the views of the local residents. This indicates that managing water in a global change scenario must consider the local population and the different actors that may play a role, be interested in, or be affected by, changes in water use or availability. For

instance, McNeeley et al. (2016) showed how a bottom-up approach to understand drought complemented the more classical top-down one and suggested that social–ecological contexts defined by both management types are important to understand how drought was experienced by local inhabitants. Again, Postigo (2014) suggested that the sustainable management of a glacier in the Peruvian Andes may be better addressed strengthening institutions and fostering local knowledge renewal. Moreover, technology and disturbances (equilibrium properties) are also often considered. This indicates that developing technology for the provisioning of water and preventing natural disasters will be key to avoid conflicts related to water.

Contrary to what Rissman and Gillon (2017) found in a systematic review of SES research, we found biodiversity to be equally addressed in comparison to other elements in mountain SES studies. This is perhaps because mountains are biodiversity hot-spots and host many endemic species (Payne et al. 2020). Mountains are also among the most threatened ecosystems by climate change (Hock et al. 2019), especially at high elevations, where changes in temperature are higher (Hock et al. 2019). This probably was reflected in our data, since climate patterns and equilibrium properties (which includes frequency, timing, extent, and magnitude of disturbances) are both addressed when biodiversity is the target sector. Again, our analyses also suggest that when dealing with biodiversity and climate change, it's important to include the knowledge of the SES by the stakeholders, as well as who is responsible (or partially responsible) for local rules affecting biodiversity, or which sectors may need to play a higher role when managing biodiversity in mountains. For example, Cottrell et al. (2020) show how taking into account these attributes can help manage the mountain pine beetle (*Dendroctonus ponderosae*) in western USA.

Our analysis identified attributes related to the institutions managing the resources in most sectors. Notably, rule-making organizations and their network structure appear among the most frequently addressed and interconnected attributes. These institutional components are intricately linked with equilibrium properties and the mental models of actors involved in resource management. The connection between institutions and elements affecting equilibrium properties, such as natural disasters, highlights the importance of considering management institutions when dealing with these challenges. Similarly, the frequent association of institutions with the diverse mental models of actors shows the importance of ensuring that rule-making organizations are suited to accommodate the needs of those they impact. This can ensure that contrasting and often conflicting viewpoints are considered in management planning, a key aspect to prevent maladaptation (Magnan et al. 2016).

Unaddressed elements

Out of the 49 attributes considered in this paper, only six of them were never used in any of the reviewed manuscripts. Some of these may be contextually nuanced, such as distinctive characteristics (RU6) or historical continuity (GS10), making them hard to identify and code. The rest are all related to socioeconomic drivers, such as political stability, media organizations, or technology. Among those socioeconomic drivers that were addressed in the reviewed works, such as economic development of demographic trends, they appeared scarcely. Thus, the reviewed works almost always considered local socioeconomic variables, particularly governance systems and actors, but global socioeconomic drivers were not as often addressed.

Following Ostrom's SES framework, global socioeconomic driver attributes refer to external political, economic, and social elements impacting the social–ecological system (Ostrom 2007, 2009). The fact that these attributes did not appear in our database does not necessarily mean that they are not relevant in mountain regions. Not considering the global economic and political agenda is hardly realistic in a globalized world, as globalization can have impacts on the connectedness, intensity, and speed of interactions among variables of any social–ecological system (Young et al 2006). Moreover, as globalization is a relatively recent phenomena, the lack of past experience makes it even more difficult to anticipate the potentially wide range of consequences linked to it (Young et al 2006). Thus, we encourage future researchers to combine variables related to local governance with global socio-economic and political drivers to successfully develop effective adaptation strategies in the long run.

Additionally, there are some attributes which were seldomly addressed. For instance, despite that mountains offer new opportunities for entrepreneurs (Covaci and Brejea 2020; Martini et al 2020), we found very few works dealing with leadership or entrepreneurship (A5). The urgent need for diversification of the winter tourism (Bausch and Gartner 2020; Hoy et al. 2011), the higher availability of internet services in remote areas, the increase of work-from-home possibility in many sectors after the COVID19 pandemic (Bick et al. 2021), and the incentivization of circular and local economies in many regions of the world (Heshmati 2016; Urbinati et al. 2017), offer a plethora of new business models that seem not to be fully addressed by the scientific community. We advocate for the further inclusion of entrepreneurship in SES approaches, because all the above-mentioned points may have an impact in the whole region. For example, promoting the use of local wood for heating can be seen as a good adaptive strategy under a circular economy development pathway (Pan et al 2015), but the logging can have detrimental effects on large mammal populations inhabiting local forests (Bowman et al. 2010; Brodie et al.

2015), which in its turn may affect grassland biodiversity by limiting or removing the effect of grazing (Riesch et al. 2019; Tälle et al. 2016).

Conclusions

Despite that mountains are tightly connected with the lowlands, these regions are physically, socially, and often culturally distinct from them, and their current state is the legacy of thousands of years of interactions between humans and nature (Olsson et al. 2000; Telbisz et al. 2016). The network of interactions that make up this socio-ecological system is an exceptional framework for deepening the application of SES approaches. However, mountain SES research is still a work in progress, and in our analysis, we identified potential caveats and opportunities for future research. Future development must be focused on collecting empirical data at finer spatial and temporal scales, as well as on developing analytical tools and advancing frameworks to effectively integrate both socio-economic and ecological variables in SES research. Additionally, we encourage researchers to incorporate relevant but understudied attributes in their future mountain SES studies, such as entrepreneurship and global socio-economic and political drivers, to prevent negative effects of a priori good adaptive solutions. Finally, our review identified many frameworks available to study mountain regions from different perspectives. To take advantage of their different approaches, multiple frameworks can be combined to exploit the strengths of each of them.

References

Aceves-Bueno E, Adeleye AS, Bradley D, Tyler Brandt W, Callery P, Feraud M et al (2015) Citizen science as an approach for overcoming insufficient monitoring and inadequate stakeholder buy-in adaptive management: criteria and evidence. Ecosystems 18(3):493–506

Adger WN (2006) Vulnerability. Glob Environ Change 16(3):268–281

Alessa L, Kliskey A, Altaweel M, Barton M, Bankes S, Bondizio E, Brown D, Rogers D (2015) Best practices integrating social sciences into social ecological systems science: future directions for building a more resilient America. Center for Resilient Communities, University of Idaho, Moscow

Al-Kalbani MS, Price MF, O'Higgins T, Ahmed M, Abahussain A (2016) Integrated environmental assessment to explore water resources management in Al Jabal Al Akhdar Sultanate of Oman. Reg Environ Change 16(5):1345–1361. https://doi.org/10.1007/s10113-015-0864-4

Ballard HL, Dixon CGH, Harris EM (2017) Youth-focused citizen science: examining the role of environmental science learning and agency for conservation. Biol Cons 208:65–75

Barrio IC, Herrero J, Guillermo Bueno C, López BC, Aldezabal A, Campos-Arceiz A, García-González R (2013) The successful introduction of the alpine marmot Marmota marmota in the Pyrenees, Iberian Peninsula Western Europe. Mammal Rev 43(2):142–155

Bausch T, Gartner WC (2020) Winter tourism in the European Alps: is a new paradigm needed? J Outdoor Recreat Tour 31:100297

Berkes F, Folke C (1998) Linking social and ecological systems for resilience and sustainability. Link Soc Ecol Syst: Manag Pract Soc Mech Build Resil 1(4):4

Berkes J, Folke C, Colding J (2003) Navigating social-ecological systems building resilience for complexity and change. Cambridge University Press. https://doi.org/10.1017/CBO9780511541957.020

Bick A, Blandin A, Mertens K (2021) Work from home before and after the COVID-19 outbreak. Available at SSRN 3786142

Binder CR (2007) From material flow analysis to material flow management part I: social science modeling approaches coupled to MFA. J Clean Prod 15:1596–1604. https://doi.org/10.1016/j.jclepro.2006.08.006

Binder CR, Hinkel J, Bots PWG, Pahl-Wostl C (2013) Comparison of frameworks for analyzing social-ecological systems. Ecol Soc 18(4):26. https://doi.org/10.5751/ES-05551-180426

Blumstein DT, Pelletier D (2005) Yellow-bellied marmot hiding time is sensitive to variation in costs. Can J Zool 83(2):363–367. https://doi.org/10.1139/z05-020

Bowman J, Ray JC, Magoun AJ, Johnson DS, Dawson FN (2010) Roads, logging, and the large-mammal community of an eastern Canadian boreal forest. Can J Zool 88(5):454–467

Brodie JF, Giordano AJ, Ambu L (2015) Differential responses of large mammals to logging and edge effects. Mamm Biol 80(1):7–13

Brun F, Berthier E, Wagnon P, Kääb A, Treichler D (2017) A spatially resolved estimate of High Mountain Asia glacier mass balances, 2000–2016 Nat. Geosci 10:668–673

Brymer ALB, Holbrook JD, Niemeyer RJ, Suazo AA, Wulfhorst JD, Vierling KT, Newingham BA, Link TE, Rachlow JL (2016) A social-ecological impact assessment for public lands management: application of a conceptual and methodological framework. Ecol Soc 21(3):9. https://doi.org/10.5751/ES-08569-210309

Butts C (2020) _network: Classes for Relational Data_. The Statnet Project (<URL: http://www.statnet.org>). R package version 1.16.1, URL: https://CRAN.R-project.org/package=network

Butts (2020b) sna: tools for social network analysis. R package version 2.6. https://CRAN.R-project.org/package=sna

Cabello V, Willaarts BA, Aguilar M, del Moral Ituarte L (2015) River basins as social-ecological systems: linking levels of societal and ecosystem water metabolism in a semiarid watershed. Ecol Soc 20(3):20. https://doi.org/10.5751/ES-07778-200320

Capitani C, Garedew W, Mitiku A, Berecha G, Hailu BT, Heiskanen J, Hurskainen P, Platts PJ, Siljander M, Pinard F, Johansson T, Marchant R (2019) Views from two mountains: exploring climate change impacts on traditional farming communities of Eastern Africa highlands through participatory scenarios. Sustain Sci. https://doi.org/10.1007/s11625-018-0622-x

Carey M, Molden OC, Rasmussen MB, Jackson M, Nolin AW, Mark BG (2017) Impacts of glacier recession and declining meltwater on mountain societies. Ann Am Assoc Geogr 107(2):350–359

Charles A, Loucks L, Berkes F, Armitage D (2020) Community science: a typology and its implications for governance of social-ecological systems. Environ Sci Policy 106:77–86

Colding J, Barthel S (2019) Exploring the social-ecological systems discourse 20 years later. Ecol Soc 24:1

Cottrell S, Mattor KM, Morris JL, Fettle CJ, McGrady P, Maguire D, James PMA, Clear J, Wurtzebach Z, Wei Y, Brunelle A, Western J, Maxwell R, Rotar M, Gallagher L, Roberts R (2020) Adaptive capacity in social-ecological systems: a framework for addressing bark beetle disturbances in natural resource management. Sustain Sci 15(2):555–567

Covaci B, Brejea R (2020) Economic development of the European mountain area between 2014–2018: a statistical approach. Annals of the Academy of Romanian Scientists 9:2/2020

Crain R, Cooper C, Dickinson JK (2014) Citizen science: a tool for integrating studies of human and natural systems. Ann Rev Environ Resour 39:641–665

Danielsen F, Pirhofer-Walzl K, Adrian TP, Kapijimpanga DR, Burgess ND, Jensen PM, Madsen J et al (2014) Linking public participation in scientific research to the indicators and needs of international environmental agreements. Conserv Lett 7(1):12–24

Daugstad K (2019) Resilience in mountain farming in Norway. Sustainability 11(12):3476. https://doi.org/10.3390/su11123476

de Groot RS, Wilson MA, Boumans RM (2002) A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecol Econ 41(3):393–408

del Mar Delgado-Serrano M, Ramos P (2015) Making Ostrom's framework applicable to characterize social ecological systems at the local level. Int J Commons 9(2):808

Dussaillant I et al (2019) Two decades of glacier mass loss along the Andes. Nat Geosci 12:802–808

Eakin H, Tompkins EL, Nelson DR, Anderies JM (2009) Hidden costs and disparate uncertainties: trade-ofs in approaches to climate policy. In: Adger NW, Lorenzoni I, Brien OK (eds) Adapting to climate change: thresholds, values, and governance. Cambridge University Press, Cambridge

Elsen PR, Monahan WB, Merenlender AM (2020) Topography and human pressure in mountain ranges alter expected species responses to climate change. Nat Commun 11:1974. https://doi.org/10.1038/s41467-020-15881-x

Environmental European Agency EEA (2016) Europe's ecological backbone: recognising the true value of our mountains. ISBN 978-92-9213-108-1 ISSN 1725–9177 https://doi.org/10.2800/43450. Luxembourg: Office for Official Publications of the European Union

Epstein G, Vogt JM, Mincey SK, Cox M, Fischer B (2013) Missing ecology: integrating ecological perspectives with the social-ecological system framework. Int J Commons 7(2):432–453

Everard M, Gupta N, Chapagain PS, Shrestha BB, Preston G, Tiwari P (2018) Can control of invasive vegetation improve water and rural livelihood security in Nepal? Ecosyst Serv 32:125–133. https://doi.org/10.1016/j.ecoser.2018.07.004

FAO (2011) Why invest in sustainable mountain development? Rome, Italy: Food and Agriculture Organization of the United Nations (FAO). http://www.fao.org/docrep/015/i2370e/i2370e.pdf

FAO (2015) Mapping the vulnerability of mountain peoples to food insecurity. Romeo, R., Vita, A., Tes-tolin, R. & Hofer, T., eds. Rome, Italy. http://www.fao.org/3/a-i5175e.pdf

Filbee-Dexter K, Symons CC, Jones K, Hiag HA, Pittman J, Alexander SM, Burke MJ (2018) Quantifying ecological and social drivers of ecological surprise. J Appl Ecol 55:2135–2146

Fischer EM, Knutti R (2015) Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes. Nat Clim Change 5:560–564

Folke C (2006) Resilience: the emergence of a perspective for social–ecological systems analyses. Glob Environ Change 16(3):253–267

Folke C, Biggs R, Norström AV, Reyers B, Rockström J (2016) Social-ecological resilience and biosphere-based sustainability science. Ecol Soc 21:41

Frey UJ (2020) Putting machine learning to use in natural resource management—improving model performance. Ecol Soc 25(4):45. https://doi.org/10.5751/ES-12124-250445

Fuller AC, Harhay MO (2010) Population growth, climate change and water scarcity in the southwestern United States. Am J Environ Sci 6(3):249

Graefe A, Mueller JT, Taff BD, Wimpey J (2019) A comprehensive method for evaluating the impacts of race events on protected lands. Soc Nat Resour 32(10):1155–1170. https://doi.org/10.1080/08941920.2019.1583396

Graymore ML, Sipe NG, Rickson RE (2008) Regional sustainability: how useful are current tools of sustainability assessment at the regional scale? Ecol Econ 67(3):362–372

Grumbine RE, Xu J (2021) Mountain futures: pursuing innovative adaptations in coupled social–ecological systems. Front Ecol Environ 19(6):342–348

Guha-Sapir D, Below R, Hoyois P (2019) EM-DAT: International Disaster Database www.emdat.be

Haeberli W, Schaub Y, Huggel C (2017) Increasing risks related to landslides from degrading permafrost into new lakes in de-glaciating mountain ranges. Geomorphology 293:405–417

Herrero-Jáuregui C, Arnaiz-Schmitz C, Reyes MF, Telesnicki M, Agramonte I, Easdale MH, Schmitz MF, Aguiar M, Gómez-Sal A, Montes C (2018) What do we talk about when we talk about social-ecological systems? A literature review. Sustainability 10:2950. https://doi.org/10.3390/su10082950

Heshmati A (2016) A review of the circular economy and its implementation. Available at SSRN 2713032.

Hock R, Rasul G, Adler C, Cáceres B, Gruber S, Hirabayashi Y, Jackson M, Kääb A, Kang S, Kutuzov S, Milner A, Molau U, Morin S, Orlove B, Steltzer H (2019): High mountain areas. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. **(In press)**

Hoy A, Hänsel S, Matschullat J (2011) How can winter tourism adapt to climate change in Saxony's mountains? Reg Environ Change 11(3):459–469

Huss M et al (2017) Toward mountains without permanent snow and ice. Earth Future 5:418–435

Immerzeel WW, Van Beek LP, Bierkens MFP (2010) Climate change will affect the Asian water towers. Science 328:1382–1385

Immerzeel WW, Lutz AF, Andrade M, Bahl A, Biemans H, Bolch T et al (2019) Importance and vulnerability of the world's water towers. Nature 577(7790):364–369. https://doi.org/10.1038/s41586-019-1822-y

IPCC (2019) IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O.Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. **(In press)**

Jensen-Ryan D, Budowle R, Strauss S, Durbin T, Beeton TA, Galvin KA (2019) A cultural consensus of fire and futility: harvesting beetle-kill for wood-based bioenergy in Wyoming and Colorado. Energy Res Soc Sci. https://doi.org/10.1016/j.erss.2019.101272

Kargel JSS et al (2016) Geomorphic and geologic controls of geohazards induced by Nepal's 2015 Gorkha earthquake. Science 351:aac8353

Kirschbaum D et al (2019) The state of remote sensing capabilities of cascading hazards over high mountain Asia. Front Earth Sci. https://doi.org/10.3389/feart.2019.00197

Kiser L, Ostrom E (1982) The three worlds of action: a metatheoretical synthesis of institutional approaches in strategies of political inquiry. Strategies of political inquiry, pp 179–222

Klein JA, Tucker CM, Nolin AW, Hopping KA, Reid RS, Steger C et al (2019) Catalyzing transformations to sustainability in the world's mountains. Earth's Future 7:547–557. https://doi.org/10.1029/2018EF001024

Kohler M, Stotten R, Steinbacher M, Leitinger G, Tasser E, Schirpke U, Tappeiner U, Schermer M (2017) Participative spatial scenario analysis for alpine ecosystems. Environ Manag 60(4):679–692. https://doi.org/10.1007/s00267-017-0903-7

Kramer DB, Hartter J, Boag AE, Jain M, Stevens K, Nicholas KA, McConnell WJ, Liu J (2017) Top 40 questions in coupled human and natural systems (CHANS) research. Ecol Soc 22(2):44. https://doi.org/10.5751/es-09429-220244

Liu J, Dietz T, Carpenter SR, Alberti M, Folke C, Moran E et al (2007) Science 317(5844):1513–1516. https://doi.org/10.1126/science.1144004

López BC, Figueroa I, Pino J, López A, Potrony D (2009) Potential distribution of the alpine marmot in Southern Pyrenees. Ethol Ecol Evol 21(3–4):225–235

Ma Z, Coppock DL (2012) Perceptions of Utah ranchers toward carbon sequestration: Policy implications for US rangelands. J Environ Manage 111:78–86. https://doi.org/10.1016/j.jenvman.2012.06.016

Magnan AK, Schipper ELF, Burkett M, Bharwani S, Ziervogel G et al (2016) Addressing the risk of maladaptation to climate change. Wiley Interdiscip Rev: Clim Change 7(5):646–665

Mal S (2018) Climate change, extreme events and disaster risk reduction. Springer

Mann ME et al (2017) Influence of anthropogenic climate change on planetary wave resonance and extreme weather events. Sci Rep 7:45242

Mao Z, Centanni J, Pommereau F, Stokes A, Gaucherel C (2021) Maintaining biodiversity promotes the multifunctionality of social-ecological systems: holistic modelling of a mountain system. Ecosyst Serv 47:101220

Martin LJ, Blossey B, Ellis E (2012) Mapping where ecologists work: biases in the global distribution of terrestrial ecological observations. Front Ecol Environ 10:195–201

Martínez I, González-Taboada F, Wiegand T, Camarero JJ, Gutiérrez E (2012) Dispersal limitation and spatial scale affect model-based projections of Pinus uncinata response to climate change in the Pyrenees. Glob Change Biol 18:1714–1724. https://doi.org/10.1111/j.1365-2486.2012.02660.x

Martini U, Malacarne K, Sp P, Buffa F (2020) Sustainable tourism development in rural and marginal areas ans opportunities for female entrepreneurship: lessons from an exploratory study. Worldw Hosp Tour Themes 12(4):421–430

McCord P, Dell'Angelo J, Baldwin E, Evans T (2017) Polycentric transformation in kenyan water governance: a dynamic analysis of institutional and social-ecological change. Policy Stud J 45(4):633–658. https://doi.org/10.1111/psj.12168

McGinnis MD, Ostrom E (2014) Social-ecological system framework: initial changes and continuing challenges. Ecol Soc 19(2):30. https://doi.org/10.5751/ES-06387-190230

McNeeley SM, Beeton TA, Ojima DS (2016) Drought risk and adaptation in the interior United States: understanding the importance of local context for resource management in times of drought. Weather Clim Soc. https://doi.org/10.1175/WCAS-D-15-0042.1

Mengist W, Soromessa T, Legese G (2020) Ecosystem services research in mountainous regions: a systematic literature review on current knowledge and research gaps. Sci Total Environ 702:134581

Meybeck MP, Green P, Vörösmarty J (2001) A new topology for mountains and other relief classes: an application to global continental water resources and population distribution. Mt Res Dev 21(1):34–45

Morán-Ordóñez A, Bugter R, Suarez-Seoane S, de Luis E, Calvo L (2013) Temporal changes in socio-ecological systems and their impact on ecosystem services at different governance scales: a case study of Heathlands. Ecosystems 16(5):765–782

Newell B, Crumley CL, Hassan N, Lambin EF, Pahl-Wostl C, Underdal A, Wasson R (2005) A conceptual template for integrative human–environment research. Glob Environ Change 15:299–307

Olsson EGA, Austrheim G, Grenne SN (2000) Landscape change patterns in mountains, land use and environmental diversity, Mid-Norway 1960–1993. Landsc Ecol 15(2):155–170

Orchard S, Glover D, Thapa Karki S, Ayele S, Debashish S, Roshan R, Rowhani P (2020) Exploring synergies and trade-offs among the sustainable development goals: collective action and adaptive capacity in marginal mountainous areas of India. Sustain Sci 15(6):1665–1681. https://doi.org/10.1007/s11625-019-00768-8

Ostrom E (2007) A diagnostic approach for going beyond panaceas. Proc Natl Acad Sci 104(39):15181–15187. https://doi.org/10.1073/pnas.0702288104

Ostrom E (2009) A general framework for analyzing sustainability of social-ecological systems. Science 325:419–422. https://doi.org/10.1126/science.1172133

Pan SY, Du MA, Huang IT, Liu IH, Chang EE, Chiang PC (2015) Strategies on implementation of waste-to-energy (WTE) supply chain for circular economy system: a review. J Clean Prod 108:409–421

Partelow S (2018) A review of the social-ecological systems framework: applications, methods, modifications, and challenges. Ecol Soc 23(4):36. https://doi.org/10.5751/ES-10594-230436

Payne D, Spehn EM, Prescott GW, Geschke J, Snethlage MA, Fischer M (2020) Mountain biodiversity is central to sustainable development in mountains and beyond. One Earth 3(5):530–533

Perez-León N, Bruzzone O, Easdale MH (2020) Framework to tackling the synchrony between social and ecological phases of the annual cyclic movement of transhumant pastoralism. Sustainability. https://doi.org/10.3390/su12083462

Postigo JC (2014) Perception and resilience of Andean populations facing climate change. J Ethnobiol 34(3):383–400

Poteete AR, Ostrom E (2008) Fifteen years of empirical research on collective action in natural resource management: struggling to build large-N databases based on qualitative research. World Dev 36(1):176–195

Rahbek C, Borregaard MK, Colwell RK, Dalsgaard B, Holt BG, Morueta-Holme N et al (2019) Humboldt's enigma: what causes global patterns of mountain biodiversity? Science 365(6458):1108–1113

Refulio-Coronado S, Lacasse K, Dalton T, Humphries A, Basu S, Uchida H, Uchida E (2021) Coastal and marine socio-ecological

systems: a systematic review of the literature. Front Mar Sci 8:648006

Rescia AJ, Pons A, Lomba I, Esteban C, Dover JW (2008) Reformulating the social-ecological system in a cultural rural mountain landscape in the Picos de Europa region (northern Spain). Landsc Urban Plan 88:23–33

Richman SK, Levine JM, Stefan L, Johnson CA (2020) Asynchronous range shifts drive alpine plant–pollinator interactions and reduce plant fitness. Glob Change Biol 26(5):3052–3064

Riesch F, Tonn B, Meißner M, Balkenhol N, Isselstein J (2019) Grazing by wild red deer: management options for the conservation of semi-natural open habitats. J Appl Ecol 56(6):1311–1321

Rissman AR, Gillon S (2017) Where are ecology and biodiversity in social–ecological systems research? A review of research methods and applied recommendations. Conserv Lett 10(1):86–93

Rodríguez-Rodríguez D, Bertzky B, Butchart S, Foster M (2011) Progress towards international targets for protected area coverage in mountains: a multi-scale assessment. Biol Conserv 144:2978–2983

Stritith A, Bebi P, Grêt-Regamey A (2020) Mountain forest ecosystem services—maintaining resilience in the face of disturbances. In: 22nd EGU General Assembly, held online 4–8 May, 2020, id.21291

Suckall N, Tompkins EL, Nicholls RJ, Kebede AS, Mensah A et al (2018) A framework for identifying and selecting long term adaptation policy directions for deltas. Sci Total Environ 633:946–957

Tälle M, Deák B, Poschlod P, Valkó O, Westerberg L, Milberg P (2016) Grazing vs. mowing: a meta-analysis of biodiversity benefits for grassland management. Agr Ecosyst Environ 222:200–212

Tanguay L, Bernard S (2020) Ecoagricultural landscapes in the dieng mountains of central Java; A study of their evolution and dynamics. J Rural Stud 77:169–184. https://doi.org/10.1016/j.jrurstud.2020.05

Telbisz T, Imecs Z, Mari L, Bottlik Z (2016) Changing human-environment interactions in medium mountains: the Apuseni Mts (Romania) as a case study. J Mt Sci 13(9):1675–1687

UNEP, GRID-Arendal, GMBA and MRI (2020) Elevating mountains in the post-2020 Global Biodiversity Framework 2.0

Urban (2020) Mountain linguistics. Lang Linguist Compass. https://doi.org/10.1111/lnc3.12393

Urbinati A, Chiaroni D, Chiesa V (2017) Towards a new taxonomy of circular economy business models. J Clean Prod 168:487–498

Vanclay F (2002) Conceptualising social impacts. Environ Impact Assess Rev 22(3):183–211

Viviroli D, Dürr HH, Messerli B, Meybeck M, Weingartner R (2007) Mountains of the world, water towers for humanity: typology, mapping, and global significance. Water Resour Res 43:1–13

Viviroli D et al (2011) Climate change and mountain water resources: overview and recommendations for research, management, and policy. Hydrol Earth Syst Sci 15:471–504

Vogt JM, Epstein GB, Mincey SK, Fischer BC, McCord P (2015) Putting the "E" in SES: unpacking the ecology in the Ostrom social-ecological system framework. Ecol Soc 20(1):55. https://doi.org/10.5751/ES-07239-200155

Wallrapp C, Keck M, Faust H (2019) Governing the yarshagumba 'gold rush': a comparative study of governance systems in the Kailash Landscape in India and Nepal. Int J Commons 13(1):455–478. https://doi.org/10.18352/ijc.884

Young SL, Kettenring KM (2020) The social-ecological system driving effective invasive plant management: two case studies of non-native Phragmites. J Environ Manag 267:110612. https://doi.org/10.1016/j.jenvman.2020.110612

Young OR, Berkhout F, Gallopin GC, Janssen MA, Ostrom E, Van der Leeuw S (2006) The globalization of socio-ecological systems: an agenda for scientific research. Glob Environ Change 16(3):304–316

Yu Y, Li J, Zhou Z, Ma X, Zhang X (2021) Response of multiple mountain ecosystem services on environmental gradients: how to respond, and where should be priority conservation? J Clean Prod. https://doi.org/10.1016/j.jclepro.2020.123264

Zhang H, Gao Y, Hua Y, Zhang Y, Liu K (2019) Assessing and mapping recreationists' perceived social values for ecosystem services in the Qinling Mountains. China. Ecosyst Serv 39:101006. https://doi.org/10.1016/j.ecoser.2019.101006