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REVIEW

Community-based responses for tackling environmental and socio-economic change and impacts in mountain social–ecological systems

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Abstract Mountain social–ecological systems (SES) are often rich in biological and cultural diversity with sustained human–nature interactions. Many mountain SES are experiencing rapid environmental and socio-economic change, demanding viable action for conservation to sustain ecosystem services for the benefit of their communities. This paper is a synthesis of 71 case studies of mountain-specific SES, submitted to the International Partnership for the Satoyama Initiative (IPSI) that identifies major drivers of change, associated impacts, and response strategies. We find that overexploitation, land use change, demographic change, and the regional economy are the most prevalent drivers of change in the IPSI mountain SES, leading to negative consequences for biodiversity, livelihoods, indigenous knowledge, and culture. To counter these challenges in the study SES, stakeholders from the public, private, and civil society sectors have been implementing diverse legal, behavioral, cognitive, technological, and economic response strategies, often with strong community participation. We outline the lessons learned from the IPSI case studies to show how community-based approaches can contribute meaningfully to the sustainable management of mountain landscapes.

Keywords Biodiversity conservation · Community engagement · Social–ecological systems · Sustainability · Traditional and local knowledge (TLK)

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INTRODUCTION

Mountain areas account for 22% of the world's land surface and are home to 915 million people, roughly 13% of the global population (FAO 2015a). Many mountain landscapes exhibit rich cultural and biological diversity and could be viewed as social–ecological systems (SES)[1] that provide multiple ecosystem services, contributing to the well-being of local and downstream communities (Grêt-Regamey et al. 2012; Briner et al. 2013; Khan et al. 2013; IPBES 2019a; Ngwenya et al. 2019; Seidl et al. 2019; Xu et al. 2019). The significant role of mountain landscapes for conserving biodiversity and sustaining human well-being was recognized in Chapter 13 of Agenda 21 (UNEP 1992). Indeed, mountain landscapes have been understood and featured as SES in most global and regional ecosystem assessments including the Millennium Ecosystem Assessment (MA) and the assessment reports of the Intergovernmental Science-Policy Platform for Biodiversity and Ecosystem Services (IPBES) (MA 2005; IPBES 2018b, 2019a).

Globally, it is estimated that the major land uses encountered in mountain landscapes are barren land (33%), grassland (25%), forest (25%), cropland (7%), and protected areas (10%), commonly used for livestock grazing, forestry, and other ecosystem-based livelihoods (Akramov

[1] Social-ecological Systems (SES) consist of human and ecological elements that are tightly interlinked and closely interacting (Berkes and Folke 1998). In SES, ecosystem processes and functions and services both affect and are affected by human activity, and vice versa. As a result, in order to understand the function of (and change in) SES, it is important to understand their ecological and human dimensions, as well as their interrelations. Over time, SES concept has evolved to cover interdependence, mutual dependence, and interactions between social and ecological systems (Colding and Barthel 2019).

et al. 2010). While mountain landscapes have complex interlinkages with other ecosystems globally (Ngwenya et al. 2019), they are often ecologically fragile and are affected by land use change, climate change, overexploitation of forest resources, intensive grazing, agricultural expansion, invasive species, economic change, and the expansion of settlements and population, to mention some (Sharma et al. 2008; Spehn et al. 2010; Briner et al. 2013; Schirpke et al. 2017; IPBES 2018b; IPBES 2019a; Seidl et al. 2019; Schirpke et al. 2021). As a result, many mountain SES can be quite vulnerable to change (UN 2002; ICIMOD 2010; FAO 2015a), which profoundly affects the natural resources and ecosystem services they provide to both local communities and lowland populations (Beniston 2003). Change in mountain SES can have far-reaching impacts even beyond mountain areas (Grêt-Regamey et al. 2012).

Many of these SES are home to mountain communities[2] that are economically poor, isolated, marginalized, and have a poor connection to urban areas (Jodha 2000; Price 2004; Hunzai et al. 2011), depending heavily on increasingly vulnerable forest-, livestock- and agriculture-based livelihoods (Hunzai et al. 2011; IIED 2016; Shahzad et al. 2019). Such livelihoods are often precarious considering that mountain soil is generally more vulnerable and less productive as compared to lowland soil (FAO 2015b), is prone to soil erosion and landslides, and faces constraints on the types of crops that it can accommodate. With mountain SES (and their communities) increasingly experiencing the compounding impacts of climate change, land degradation, natural disasters, and socio-economic transformation (FAO 2017), it is important to appreciate how local communities respond (Schaaf 2008; Wester et al. 2018; Xenarios et al. 2019). However, there is little information in the literature addressing the influence of risk perception in mountain areas on communities' responses to environmental change (Schneiderbauer et al. 2021). In any case, such environmental changes are already jeopardizing the livelihoods of mountain communities and trigger migration, and other social distresses (McLeman 2017).

When considering the above, there have been calls for the development and implementation of integrated approaches for the conservation and management of mountain SES (Alessa et al. 2018). Community-based approaches[3] that entail the active participation of communities have great potential toward this end. The UN General Assembly has recognized that although mountain communities suffer from marginalization, poverty, food and nutrition insecurity, social exclusion, and environmental degradation, it has also acknowledged that many of them have developed sustainable approaches to use and manage natural resources (UN 2015). For example, many mountain communities, and especially those relying on traditional forest- and agriculture-based livelihoods, have developed traditional and local knowledge (TLK) based on their observations of the linkages between changing environmental conditions and biodiversity and have used it to adapt to environmental change over generations (Delgado-Serrano et al. 2015; Ingty 2017). Such TLK often embodies memories of the past and offers cultural continuity with the future while providing guidance for effective governance and management (Jacobs 2021).

One effort to engage local communities and mobilize their TLK for landscape conservation and SES sustainability has been made through the International Partnership for the Satoyama Initiative (IPSI), launched at the 10th Conference of the Parties to the Convention on Biological Diversity (CBD COP10). IPSI's mandate is to share knowledge and create synergies among organizations and networks committed to conserving and supporting SES. As a knowledge facilitation hub, it serves to collect information from SES around the world to promote research, distill lessons, and increase awareness on the sustainable use of biological resources (CBD 2010). Some of the IPSI case studies have explored how the design and implementation of community-based SES management approach capitalizing on diverse livelihood-based and social-cultural response options can offer pathways to realize resilient and sustainable societies (Gu and Subramanian 2014; Kozar et al. 2019).

This paper synthesizes information from the 71 mountain-specific case studies submitted to the IPSI. The overall aim is to highlight what causes a change in mountain SES (and its outcomes) while also identifying strategies that have improved local livelihoods by addressing change through community-based approaches. This synthesis reflects some on-the-ground solutions to sustainable

[2] For the purpose of this paper, we define "mountain communities" as the indigenous or local communities settled in mountain SES. Many mountain communities depend directly on forest-, livestock- and agriculture-based production systems for their livelihoods. However, mountain communities are quite diverse and in some geographical or socio-economic contexts they might depend on other means of livelihood such as tourism.

[3] Community-based approaches to the conservation and management of SES are essentially voluntary initiatives of "*natural resources or biodiversity protection conducted by, for, and with the local community*" (Western et al. 1994) aiming "*to enhance wildlife/biodiversity conservation and to provide incentives, normally economic, for local people*" (Campbell and Vainio-Mattila 2003). Even though there is no single definition or "model" to community-based approaches, they are generally characterized by high levels of community engagement through local stakeholder involvement, public participation and TLK mobilization (Ruiz-Mallén and Corbera 2013; Delgado-Serrano et al. 2015).

management of mountain SES capitalizing on community engagement. With its broad view, this synthesis bridges some gaps in the current literature that mostly tends to focus on single or limited case studies and/or thematic areas of mountain landscapes (Kohler et al. 2017; Ngwenya et al. 2019; Sarmiento and Cotacachi 2019; Xenarios et al. 2019; Chapagain and Aase 2020). This would fill gaps in the current scattered knowledge about change and responses in mountain areas to help achieve the Sustainable Development Goal (SDG) 15.4 on the conservation of mountain ecosystems and their biodiversity (UN 2015), as well as contribute to international debates on the inclusion of mountain landscape conservation in both climate- and biodiversity-related policies (Makino et al. 2019; UNEP and GRID Arendal 2020).

This synthesis starts by outlining the approach used to extract and synthesize the knowledge from the IPSI case studies, especially using the modified Drivers, Pressures, Impacts, and Responses framework (see Methodology). The Results and Discussion section outlines the direct and indirect drivers, pressures, impacts, responses, and the interlinkages and dynamics of these elements. The latter section presents the key lessons learned and possible pathways to sustainability through community engagement.

METHODOLOGY

Selection of case studies

For this synthesis, we initially scanned all 197 case studies submitted by the members of the IPSI[4] between January 2011 and July 2020 to identify the mountain-specific cases (71 in total). All these case studies are available on the IPSI database website (IPSI Secretariat 2020). The only selection criterion for inclusion in the synthesis was that the underlying SES is located in a mountain area, which helped ensure the broadest possible sample of mountain SES in the synthesis. Of the 71 case studies, approximately 58% were from Asia, 18% from South and Central America, 12% from Europe, 6% from Africa, and 6% from the rest of the world, representing almost all major mountain areas and climatic zones (Fig. 1) (Table S1 contains a full list and basic information of the 71 case studies).

The IPSI format of case studies includes information about the type of ecosystem, major threats to human–nature relationships in the region, and activities carried out and its result, including lessons learned. All IPSI case studies, including those considered in this synthesis, share some common characteristics such as that they represent:

- rural areas with production activities that involve human interactions with nature;
- dynamic mosaics of different habitats (forest, agriculture, wetlands, etc.);
- ecosystem-dependent livelihoods affected by environmental and socio-economic changes; and
- conscious efforts to restore mutually beneficial human–nature relationships.

IPSI case studies represent only specific types of SES, many of which are managed by local communities or multiple stakeholders using community-based approaches. Still, they offer deep insights into how production activities related to agriculture, livestock, forestry, and fisheries can help maintain biodiversity and ecosystem services while sustainably supporting the livelihoods and well-being of local communities (IPSI Secretariat 2010; UNU-IAS and IGES 2018). Such case studies have particular relevance for conservation in terms of ways to engage communities meaningfully and thus present possible pathways toward sustainability. In this sense, these SES are the testing grounds of community and ecosystem-based approaches that are also being supported by the CBD (CBD 2018, 2019b).

Data extraction and synthesis

We extracted relevant information about the characteristics, drivers, and responses of change in the 71 IPSI mountain SES from the material included for each of them in the IPSI database. The information was extracted through manual coding of specific dimensions of change in mountain SES, which was synthesized through the Drivers-Pressures-State-Impact-Response (DPSIR) framework.

The DPSIR framework was first developed by the Organisation for Economic Co-operation and Development (OECD) as the Pressure-State-Response framework on the concept of causality (OECD 1993). The underlying logic was that human activities exert 'Pressures' on the environment and change the quality and quantity of natural resources ('State'), making the society to 'Respond' to these changes. This initial framework was further expanded, primarily by the European Environment Agency, to include the dimensions of Drivers and Impact, culminating in its current DPSIR form (Smeets and Weterings 1999; Kristensen 2004), wherein, the driving forces (D) induce pressures (P), triggering changes in its state (S), which make it experience impacts (I), activating societal responses (R) for mitigation or adaptation (Rodríguez-Labajos et al. 2009; Oesterwind et al. 2016).

[4] IPSI members include academia, government, private sector and civil society. These members submit case studies presenting the outcomes of implementation of local-level projects to conserve or restore SES in manner of living in harmony with nature.

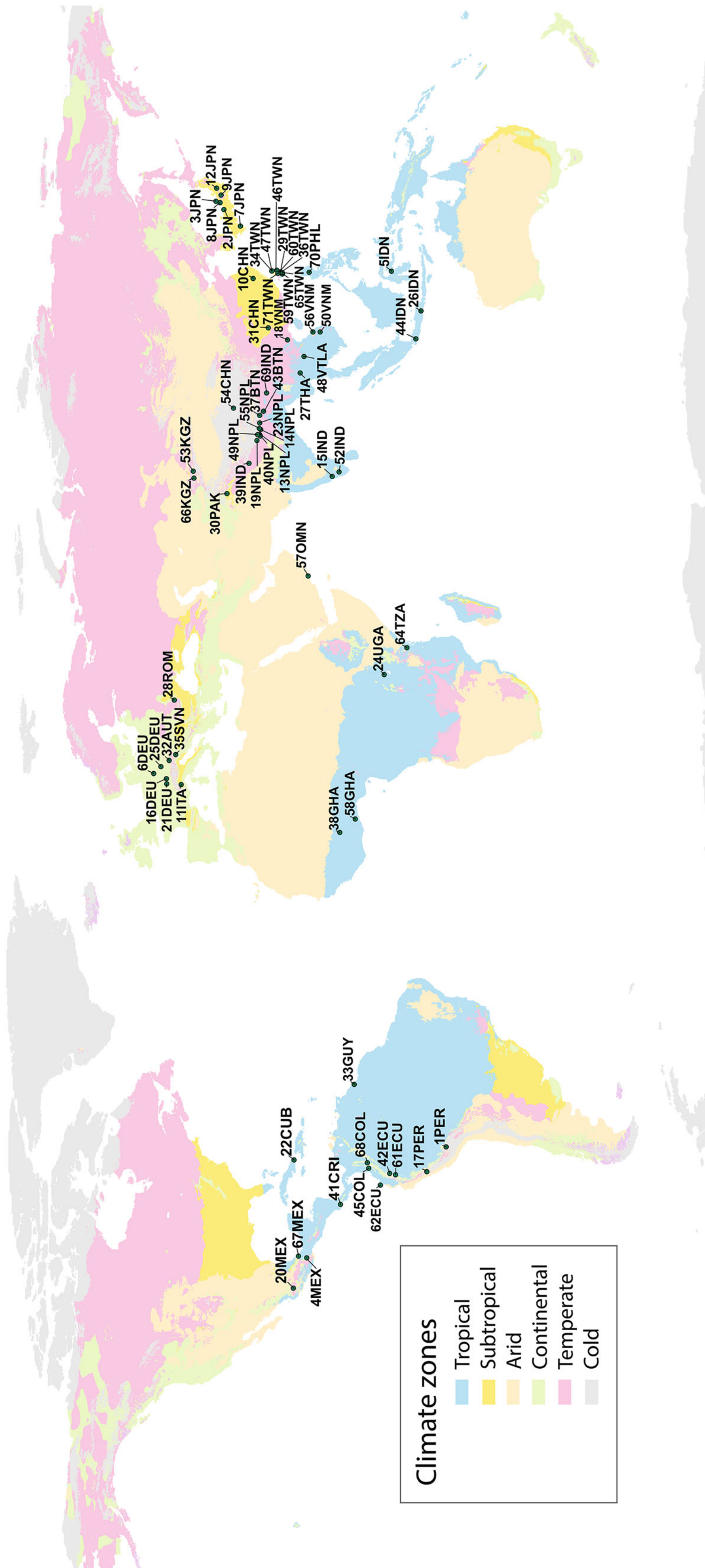

Fig. 1 Location of IPSI mountain case studies

Table 1 Definition of the DPSIR dimensions and codes used in this study

DPSIR dimensions	Definition	Codes used in this study
Drivers	Complex phenomena, whether natural or anthropogenic, governing the direction of change in an SES	Direct drivers - Land use change; overexploitation; underuse; pollution; climate change Indirect drivers - Awareness and capacity; lifestyle and culture; regional economy; demographic change
Pressures	Outcomes of a driver-initiated mechanism that may alter the environmental or socio-economic state of an SES	Deforestation; unsustainable agriculture; overgrazing; market forces; migration; urban sprawl; mindset; tourism
State	The condition of an SES (and its components) in a certain area at a specific time frame. It includes but is not confined to the physical (e.g., temperature), biological (e.g., biodiversity), chemical (e.g., pollution), or socio-economic (e.g., poverty) dimensions	Not considered in this study
Impact	Positive or negative consequences on an SES in terms of substantial environmental and/or socio-economic effects	Environmental - Biodiversity loss; land/landscape degradation; loss of habitat/mosaic; water depletion; soil degradation Social - Poverty; loss of traditional knowledge/practices; loss of culture; community shrinking; food insecurity Economic - Loss of livelihood/income; decrease in local demand; decrease in local production; decline in ecosystem services
Response	Actions or initiatives that aim to mitigate, adapt, or prevent an unwanted change or develop a positive (desirable) change	Social and behavioral - Participatory planning; capacity building; awareness generation Economic - Financial incentive, enhancement of agricultural production, livelihood diversification; Cognitive - Knowledge sharing; preservation/reintroduction of traditional varieties and practices; data platform Technological - New Technologies; new varieties/cropping patterns; yield improvement Legal - Customary; national; local

Source Definitions adapted from (Oesterwind et al. 2016); Codes for Drivers and Responses adapted from (MA 2005)

Since its inception, the DPSIR framework has been applied in many contexts around the world due to its ability to systematize and explain the change in different types of SES logically (Nassl and Löffler 2015). However, some scholars have also pointed that the distinction between DPSIR dimensions is not always clear-cut in a given context, which might result in overlapping (Oesterwind et al. 2016). In order to avoid overlapping between DPSIR dimensions, we adopt in this study the definitions proposed by Oesterwind et al. (2016) alongside the specific codes for each dimension (Table 1). Figure 2 presents a schematic representation of the logical linkages between the DPSIR dimensions. However, due to lack of information in the IPSI case studies on the environmental condition/ state of the mountain SES and its components (Table 1), we do not include the 'State' (s) dimensions in this synthesis (see Recommendations, Limitations and Future Steps).

The information used to populate the synthesis framework outlined above was extracted through the critical reading and manual coding of the IPSI case study material. The initial codes for each dimension were selected through a literature review that allowed the authors to elucidate

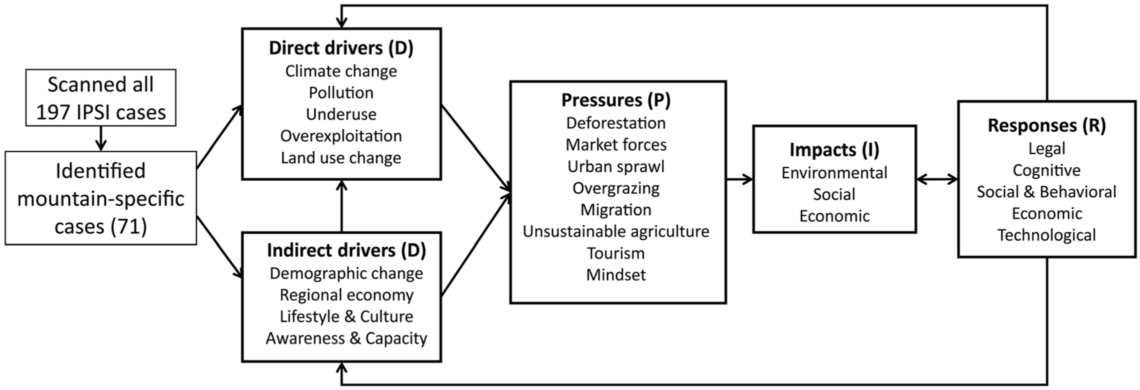

Fig. 2 Conceptual framework for the knowledge synthesis

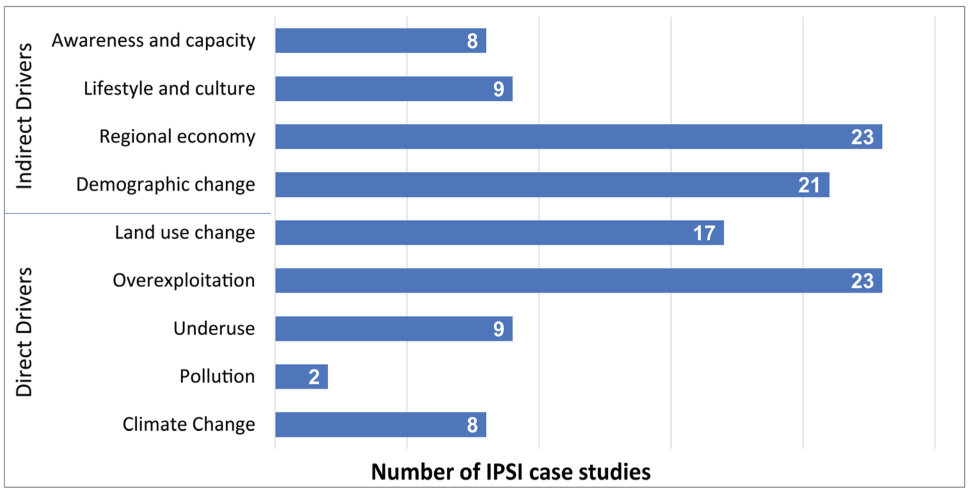

Fig. 3 Direct and indirect drivers of landscape change in the IPSI mountain case studies

better the main changes in mountain SES, and the processes through which they unfold.

The basis for the codes for the Drivers (D) of environmental change is the classification of direct and indirect drivers defined in the Millennium Ecosystem Assessment (MA 2005). The Pressures (P) and Impacts (I) are coded by the authors using a generic category of impacts that was derived through an iterative process of literature review, extraction, team consultation, and consolidation where needed, following the broad definition provided in Table 1. The Responses (R) follow the MA typology of legal, economic, social, behavioral, technological, and cognitive responses (MA 2005). These responses were further subcoded based on the specificities of the responses in the case studies, following the same iterative process used for pressures and impacts.

The information was mainly extracted by the first author, through consultation with the third author where needed. This was done to ensure the consistent extraction of the information from the base material. In order to further facilitate the reader's understanding, we use unique citations for each case study represented by country name and case study number in the order of their submission to IPSI (Fig. 2; Table S1).

RESULTS AND DISCUSSION

Drivers

Overexploitation is the most prevalent direct driver of change encountered in 23 IPSI SES, while economic and demographic changes are the major indirect drivers (Fig. 3; Table S2). Overexploitation includes the extraction of forest products and grazing beyond the natural replenishment capacity and is often linked to unsustainable agricultural practices. For example, in the Indian Western Ghats, indiscriminate forest logging for immediate monetary gains has degraded forests and wild habitats, compounding the effects of agricultural expansion and developmental projects (52IND). Regionally, overexploitation was more prominent in the mountain SES located in developing countries, particularly in the Himalaya, the Andes and mountain ranges in south-east Asia, while underuse was more prominent in developed countries such as the European Alps and the Japanese mountain villages. Overexploitation of biological resources has been identified as a major cause of species loss and habitat degradation in many other mountain landscapes (Kideghesho 2009; Khan et al. 2013; Rexhepi et al. 2013; Wang et al. 2019).

Land use change is the second most prevalent direct driver of ecosystem change observed in 17 SES and is associated with habitat loss (68COL; 69IND; 30PAK), settlement expansion (19NPL), loss of landscape mosaic (11ITA), and land degradation (65TWN; 34TWN). Similar phenomena have been reported in many other mountain landscapes (Chaudhary et al. 2017; Tarolli and Straffelini 2020). In four SES, land use change was concurrent with overexploitation, showing strong linkage between these drivers, for example, land use change primarily occurred due to a shift to unsustainable agricultural practices to increase productivity (15IND; 42ECU; 41CRI; 69IND), or to develop palm oil plantations through forest conversion (42 ECU). In addition to overexploitation, the underuse of biological resources due to land abandonment is also identified as a direct driver of environmental change as it affects natural succession and growth of trees (32AUT). This corresponds to other studies reporting land abandonment (especially agricultural land) as a major driver of environmental change in mountain landscapes (Cocca et al. 2012; Bezák and Mitchley 2014). It is worth noting that there was no particular regional trend for land use change, but like overexploitation, it was more prominent in case studies in the Himalayas and the Andes.

Climate change is one of the less prevalent direct drivers of change, as it is reported in only eight IPSI SES. In these cases, climate change is associated with (a) increased frequency of extreme events (40NPL; 43BTN), (b) loss of snow cover (24UGA), and (c) drying up of water resources (43BTN). However, the potential impacts of this driver should not be considered negligible. Although other drivers and impacts may be directly linked to climate change, it is possible that more visible challenges such as demographic change and overexploitation were often seen as more pressing, needing immediate attention to be able to deal with future climatic changes. In the academic literature, however, climate change is recognized as one of the most potent and visible drivers of environmental change in mountainous contexts (Schirpke et al. 2017; Seidl et al. 2019). Studies show that it could affect agroecosystem productivity (Briner et al. 2013), ecosystem resilience (Schirpke et al., 2017), and ecosystem services provision (Seidl et al., 2019), and induce long-term ecosystem change (UNFCCC 2014). For example, in a study in Semien mountains (Ethiopia), 70% of the local farmers felt that climate change decreased land productivity (Yohannes et al. 2020), while in another study in Pakistan, it was observed that the climate change significantly reduced ecosystem services like drinking water, food diversity, fuel wood, and non-timber forest products (Shahzad et al. 2019). The Intergovernmental Panel on Climate Change (IPCC) Special Report on the Ocean and Cryosphere (SROCC) asserts that climate change is not just affecting biodiversity and freshwater resources in mountain regions but also the food security, livelihoods, health and well-being, tourism, recreation, and culture (particularly of indigenous peoples) (Hock et al. 2019). This strongly implies that climate change may impact indirect drivers such as regional economy and culture.

Among the indirect drivers, regional economy is the most prevalent driver observed in 23 IPSI SES, and largely relates to the second most prevalent driver, demographic change, observed in 21 IPSI SES. The change in regional economy coexists with demographic change in nine SES, showing strong linkages. Together with the less dominant drivers—lifestyle and culture, and awareness and capacity—these indirect drivers compound direct drivers such as overexploitation, underuse, and land use change.

Pressures

Eight major pressures were identified that include deforestation, market forces, unsustainable agriculture, overgrazing, urban sprawl, migration, tourism and mindset (Fig. 4; Table S3).

Deforestation, unsustainable agriculture, and migration were the most prevalent and observed in 16 cases. The main reasons for deforestation include (a) ineffective administrative control, including weak enforcement of rules on forest resource use, combined with minimum afforestation[5] effort (30PAK); (b) forest clearance for subsistence agriculture (41CRI); and (c) forest clearance for commercial plantations (e.g., oil palm, eucalyptus) (42ECU; 18VNM). Deforestation occurred mainly in case studies in the Hindu-Kush Himalaya, the Andes, and in south-east Asia. Deforestation has been identified as a major pressure in other studies (Pandit et al. 2007; Hall et al. 2009; Chapagain and Aase 2020; Clerici et al. 2020), which can set in motion the loss of biodiversity and decline of local or traditional livelihoods (Díaz et al. 2006). Forest destruction, in addition to overgrazing, farmland

[5] Afforestation refers to planting new forests, while reforestation refers to replanting degraded forests that were lost due to developmental and other human or natural activities.

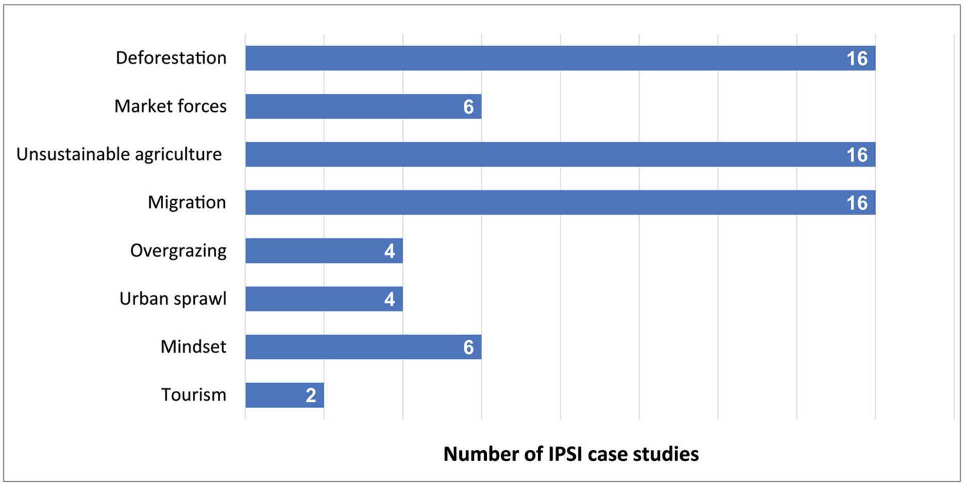

Fig. 4 Pressures on the IPSI mountain case studies

conversion, and inappropriate cropping practices in the mountain areas, has been linked to loss of livelihood of mountain communities and increases in environmental risks also in downstream areas (Hunzai et al. 2011).

The case studies show that forests are also affected by unsustainable agricultural practices that include shifting cultivation (69IND; 56VTN; 40NPL) and environmentally destructive farmland expansion (52IND; 64TZA; 68COL). Excessive fertilizer and agrochemical use (11ITA; 15IND; 34TWN) and replacement of traditional varieties with high-yielding varieties (31CHN) are also deteriorating the mountain landscape.

Migration is another widely observed pressure. Even though actual estimates were not provided, the abandonment of agricultural fields was linked to outmigration and aging in 15 cases leading to land degradation and loss of landscape mosaics. However, the reasons for outmigration did not differ much regionally and were mainly economic in nature. People migrated to cities for better opportunities (45COL) or lacked equivalent economic opportunities in these regions (2JPN; 16DEU). Farmland abandonment was mainly associated with an aging population that facilitated inevitable farm retirement (2JPN; 8JPN; 65TWN). Abandonment was a common phenomenon in both developed and developing countries. However, urban sprawl was more common in cases from developing countries (39IND; 40 NPL; 64TZA).

Many of the above findings are corroborated by the literature. For example, land abandonment is accelerating land degradation in the mountains (Tarolli and Straffelini 2020), while the neglect of traditional land management continues to alter landscape composition (Schirpke et al. 2017). Furthermore, studies in mountain regions have reported high rates of outmigration, including those in the European Alps (Perlik and Membretti 2018), the Hindu-Kush Himalaya (ICIMOD 2015), the Chilean Andes (Santiago 2017), and the Central Caucasus mountains (Kohler et al. 2017). Nearly two-thirds of the mountain region in the world is experiencing lower population growth as compared to the lowlands (Bachmann et al. 2019). This has led to labor shortages and loss of landscape mosaics since managing mountain ecosystems is labor-intensive (Seidl et al. 2019). The reasons for outmigration include poverty, food insecurity, harsh climate, and scarcity of natural resources (Bachmann et al. 2019).

Market forces also act as a major pressure, leading to unsustainable resource extraction (13NPL; 20MEX; 40NPL; 62ECU) in these already fragile areas. In some cases, market forces have induced a switch to more commercial activities like adoption of commercial crops or monocultures such as Eucalyptus plantations (18VNM). Some other related but less prevalent pressures include overgrazing (17PER; 20MEX) and tourism (20MEX; 52IND).

Finally, mindset is a very important pressure in some areas. Mindset as a pressure basically refers to the disillusionment of local communities that manifests in the exploitation or abandonment of resources they depend upon, instead of protecting them or gaining good profits from their sustainable use. Some very visible examples include the changing perception about wild varieties, increasing preference of high-yielding varieties and use of pesticides (15IND), negligence toward traditional land use and activities mostly linked to profitability (16DEU), marginalization of women (1PER), profit-seeking motivation leading to illegal harvesting of wild varieties (49NPL), and decreasing bonds with local culture. Interestingly, while mindset change was evident in many mountain regions, it is manifested through different perceptions. For example, in the Alps, it manifested through disconnect with traditional activities, and, in the Himalaya and Andes, it was more linked to illegal trading, lack of awareness, and marginalization of

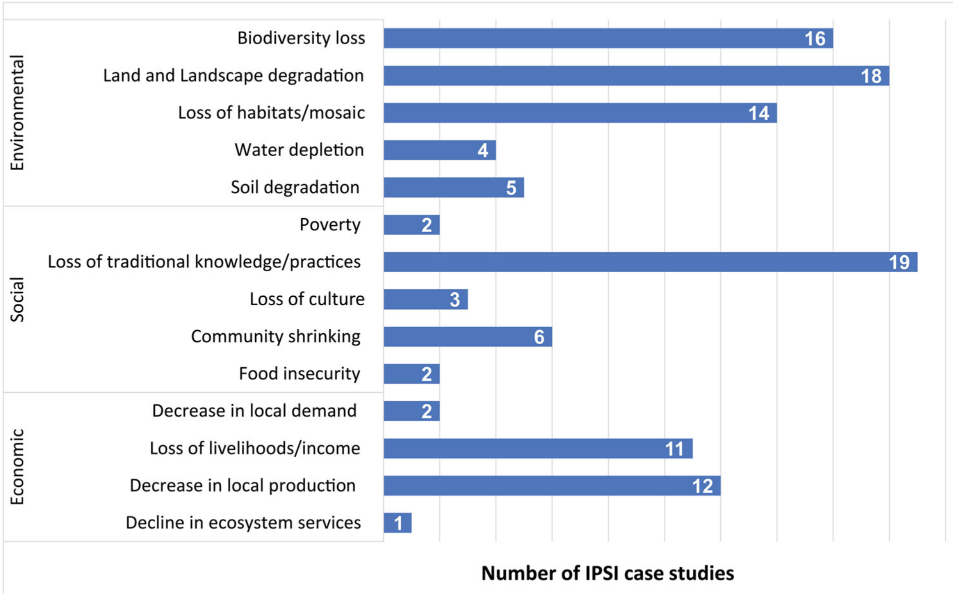

Fig. 5 Environment, social and economic impacts in the IPSI mountain case studies

women that led to decreased use of women's TLK in landscape management.

Impacts

The drivers and pressures outlined above lead to environmental, economic, and social impacts (Fig. 5; Table S4). The most prevalent environmental impacts in IPSI case studies are biodiversity loss observed in 16 cases, habitat loss observed in 14 cases, and land and landscape degradation observed in 18 cases. Biodiversity loss includes loss of agrodiversity in terms of local and traditional crop varieties of important genetic value and medicinal plants due to excessive forest logging and unregulated trade expansion. Other studies have reported similar cases of species loss or decline (Pandit et al. 2007; Hall et al. 2009; Swiderska 2020), which also means their reduced use by local and indigenous peoples for traditional or medicinal purposes (Díaz et al. 2006).

Many other studies have also identified land and landscape degradation as a major impact (McLeman 2017; IPBES 2018a; IPCC 2019; Tarolli and Straffelini 2020). Landscape degradation further triggers habitat degradation and alters wildlife and recreational value that have also been identified as major pressures in addition to changes in the regional economy in landscapes (Bonn et al. 2009).

The most prevalent social impacts are related to the erosion or loss of TLK and associated practices. This is manifested through agricultural mechanization (11ITA), lack of knowledge exchange between local communities (15IND), abandonment of orchards (16DEU) and agricultural lands (2JPN), and lack of documentation (22CUB). It is important to note that loss of TLK occurred in almost all mountain SES covered in this study, irrespective of the region. Studies have linked the erosion and decline of TLK to multiple factors such as resource use intensification (Jodha 2005) and emerging perceptions that TLK cannot tackle the new socio-economic and cultural conditions (Reyes-García et al. 2013). The case studies show that mindset is also a pressure for TLK as it drives the community toward more illegal activities for resource harvesting, eroding their cultural base (40NPL, 15 IND).

Major economic impacts include loss of livelihoods and the decline in local production, mainly of agricultural crops and timber and fruits. Local production decline is mainly due to field abandonment (3JPN), scarcity of labor (8JPN), lack of profitability (16DEU), growth in lumber imports and insufficient forest management (7JPN), outmigration (39IND; 30PAK), and forest industry stagnation (2JPN). However, loss of agricultural production is not in consonance with the highest pressure—unsustainable agricultural practices. In most cases, loss of agricultural production is either due to abandoning of the fields or loss of traditional knowledge. Loss of livelihoods and agricultural production has been reported as a major impact of environmental change across different regions (FAO 2015a, 2017; Xenarios et al. 2019; Tarolli and Straffelini 2020).

Responses

The response strategies exhibited by the IPSI case studies have been categorized into five major types—cognitive, social and behavioral, legal, economic, and technological,

Table 2 Mapping of the responses in the IPSI mountain case studies across IPBES approaches to sustainability

IPBES approaches for sustainability	Synergistic elements of IPBES and IPSI approaches	Specific responses from case studies
Enable integrative governance to ensure policy coherence and effectiveness	Facilitate multi-stakeholder and multi-sectoral linkages Mainstream biodiversity in agriculture and forestry sectors	Multi-level and local stakeholder-based approaches (59TWN) Customary law converted to statutory form including customary bans to govern natural resource use (5IDN) Participatory mapping of landscape to prepare management plan (29TWN)
Promote inclusive governance through stakeholder engagement and inclusion of indigenous and local communities	Enable participation of local and indigenous communities Promote community empowerment through enhanced role in decision-making and conservation implementation	Local community involvement in forest management (56VNM; 40NPL; 62ECU) Community conservation agreements along with protection of communal land tenure (42ECU) Support of local organizations to improve environmental governance (38GHA) Legal framework for indigenous community-based management of forests (4MEX) Implementation of afforestation policy with the help of local communities (54CHN) Empowerment of local communities (34TWN) Connection of local community groups to conservation projects (40NPL)
Practice informed governance	Encourage documentation of TLK Reintroduce traditional practices and technologies Facilitate knowledge-sharing, especially TLK	Development of local biocultural databases (1PER), Documentation of traditional knowledge and practices (41CRI; 43BTN; 50VNM) Integration of traditional knowledge and practices into community-based conservation (66KGZ) Creation of a people's biodiversity register (69IND) Technical support for traditional agriculture for boosting farm income (28ROM) Knowledge sharing at the local level (24UGA)
Promote adaptive governance and management	Enable locally tailored choices and public responsiveness, often through awareness raising, capacity building and participatory planning Promote traditional methods for climate adaptation	Establishment of community protected areas and participatory community-based land use planning (38GHA) Awareness raising on environmental change, nature conservation and coping strategies (18VNM; 25DEU) Traditional methods to cope with climate challenges, e.g., preservation of seed varieties (22CUB) and promotion resilient crop varieties (40NPL) Protection of local ownership and women empowerment (1PER; 39IND; 43BTN)
Promote sustainable production and consumption of food	Promote biodiversity-friendly agricultural practices and sustainable use of agricultural genetic resources Promote conservation of semi-natural socio-ecological production landscapes	Promotion of sustainable agricultural practices (4MEX; 19NPL) Preservation of local varieties (22CUB) Reconversion of excessively cultivated farmland to forestland (54CHN) Organic farming (39IND; 41CRI; 2JPN) Replacement of slash and burn agriculture with agroforestry (40NPL) Ecological farming practices (48VTLA) Utilization of agricultural waste (59TWN) Forest restoration and reconnection (41CRI)

Table 2 continued

IPBES approaches for sustainability	Synergistic elements of IPBES and IPSI approaches	Specific responses from case studies
Integrate multiple uses for sustainable forests	Focus on multiple values of nature Promote ecological restoration and prevention of logging Promote sustainable use of forest products	Promotion of sustainable forest use (56VNM; 7JPN) Forest protection to inhibit overexploitation (14NPL) Forest ecotourism (59TWN) Restoration of degraded forests and watershed conservation (42ECU) Restoration of degraded areas (43BTN) Sustainable collection of non-timber forest products from community-managed forests (42IND)
Conserve, manage effectively and use sustainably the terrestrial landscapes	Promote landscape-scale spatial planning Protect biodiversity beyond protected areas Promote land-based adaptation and mitigation measures	Forest management using the concept of circular economy (59TWN) Forest restoration (38GHA) Reformation of grazing practices and implementation of soil conservation measures (41CRI) Improvement of natural resource management practices and infrastructure (43BTN)
Improve the sustainability of economic and financial systems	Provide financial incentives for biodiversity protection and sustainable use Create markets for locally produced environment-friendly products	Market improvement for sustainable forest products (43BTN) Provision of financial incentives for forest protection (42ECU) Adoption of payment of ecosystem services schemes (37BTN) Designing incentive instruments for ecosystem services (16DEU), Management cooperatives for marketing local agricultural products (22CUB)

spanning 14 sub-responses. Figure 6 shows these categories with the number of IPSI case studies that exhibit the particular responses, multiple responses in many cases.

Cognitive responses focused on protecting TLK are the most prevalent (found in 27% of the IPSI case studies) and include many measures linked to TLK mobilization, such as biocultural databases, local traditional knowledge platform, promotion of traditional land use practices, re-establishing keystone species, conservation related projects, preservation and documentation of TLK and practices, and knowledge-sharing. They also include the reintroduction of traditional technologies such as mixed cropping systems like 'Kichwa chakra system' (42ECU) and 'Rice-Fish-Duck Symbiotic System' in rice terrace fields (31CHN).

Social and behavioral responses are identified in 26% of the IPSI case studies and include awareness raising, capacity building, and participatory planning. Participatory planning aims to empower local communities by encouraging co-management (34TWN) and collaboratively improving markets for sustainable forest produce (43BTN).

Legal responses are found in 16% of the IPSI case studies and include customary, national or state laws and local statutory regulations. Examples include customary bans to stop the exploitation of natural resources (5IDN), policy reforms to strengthen land markets (4MEX) and national regulations for forest protection (8JPN; 14NPL). Broadly, these legal responses have been targeted at regulating the natural resource use and curbing deforestation and were mainly undertaken by government or state-level formal institutions while also engaging, in most cases, the local community (Table 2). Legal responses were common in areas where deforestation is a major concern, such as the Hindu-Kush Himalaya, the Andes, Western Ghats, Weto Range, South-east Asian hill regions and Tanggula mountains.

Economic responses were identified in 19% of the IPSI case studies and seek to (a) improve the local livelihoods through alternative livelihood options (13NPL; 20MEX; 37BTN; 41CRI; 59TWN), (b) improve agricultural productivity (41CRI), and (c) offer financial incentives (1PER; 7JPN; 16DEU; 28ROM; 40NPL). Financial incentives include developing markets for sustainable forest produce, improving market access, creating economic incentives for forest protection, setting up regional funds, enhancing local entrepreneurship, and providing enterprise infrastructure. Financial incentives were perceived as a win–win strategy, especially in some developed areas such as the Alps, as

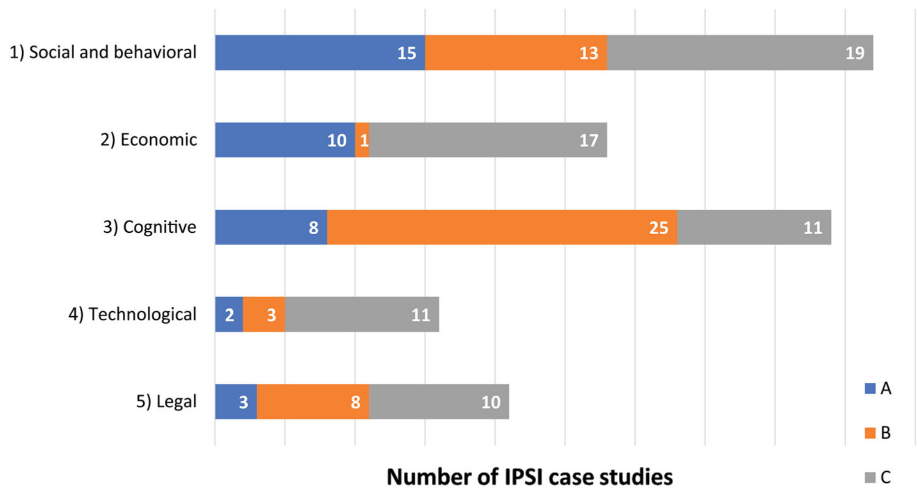

Fig. 6 Responses to SES change in the IPSI mountain case studies. Notes for (b): from top to bottom: 1. Social and Behavioral—A1: participatory planning, B1: capacity building, C1: awareness generation; 2. Economic—A2: financial incentive, B2: enhancement of agricultural production, C2: livelihood diversification; 3. Cognitive—A3: knowledge sharing, B3: preservation/reintroduction of traditional varieties and practices, C3: data platform; 4. Technological—A4: new technologies, B4: new varieties/cropping pattern, C4: yield improvement; 5. Legal—A5: customary, B5: national, C5: local

they helped bring back to abandoned landscapes people that had emigrated while at the same time restoring traditional practices.

Technological responses are identified in 12% of the IPSI case studies. Some of the examples include the introduction of (a) new techniques for agricultural yield improvement (24UGA) (b) new varieties or cropping patterns (22CUB; 40NPL), and (c) new technologies, for example, biogas generation (2JPN), silviculture techniques and technologies (10CHN) and water-efficient technology (45COL). Most technological innovations sought to engage local communities directly as a means to boost technology adoption, and they were more visible in the Himalaya, Andes, Japan and China. In these regions, economic benefits were often used to motivate local people to participate.

All these responses, except legal responses from the national government, have relied on community's participation for their implementation. In many of the SES, initial responses did not make an impact until after strengthening community's role in the initiative either through generating awareness or providing financial incentives (4MEX; 18VNM; 22CUB; 25DEU; 29TWN; 56VNM; 40NPL; 42 ECU; 42BTN; 62ECU). The following sub-section discusses the dynamics of the responses with drivers, impacts and pressures, and needs and aspects of community-based approaches.

Dynamics of drivers, pressures, impacts, and responses

Understanding the linkages between drivers and pressures and how they translate into impacts would help in figuring out how the different responses can be targeted to deal with change and assist their design to improve effectiveness. It is also essential to differentiate between multiple drivers and their interactions (Pèlachs et al. 2017), as they can further exacerbate pressures and impacts. For example, some scholars suggest that land use change is a stronger driver than climate change (Améztegui et al. 2010; Slaymaker 2010; Catalan et al. 2017). However, land use change, combined with overexploitation, may exacerbate climate change impacts (Seidl et al. 2019). Research on mountain landscapes has been considering these complex interactions between direct and indirect drivers, ecosystem services, human well-being, and institutional responses (Martín-López et al. 2019).

The analysis in the previous sections shows the linkages between various drivers, pressures and impacts, particularly between overexploitation, land use change, migration, land abandonment and regional economy evident in the IPSI case studies. Such broader linkages are summed up in Fig. 7, showing that many impacts are the combined effect of multiple drivers and pressures. Figure 7 aptly shows that the studied mountain SES are rather complex, with various drivers, pressures, and impacts continuously influencing each other. For example, in many of the study SES multiple drivers converge to cause change, but more often than not give rise to different pressures and impacts, subject to the distinct contexts of each SES. In this sense, it is nearly impossible to point out the exact causality for a particular impact. The analysis above and Fig. 7 also suggest that impacts are also interconnected. For example, the loss of traditional crop varieties may undermine livelihoods in the long run. Regional economy also drives change in

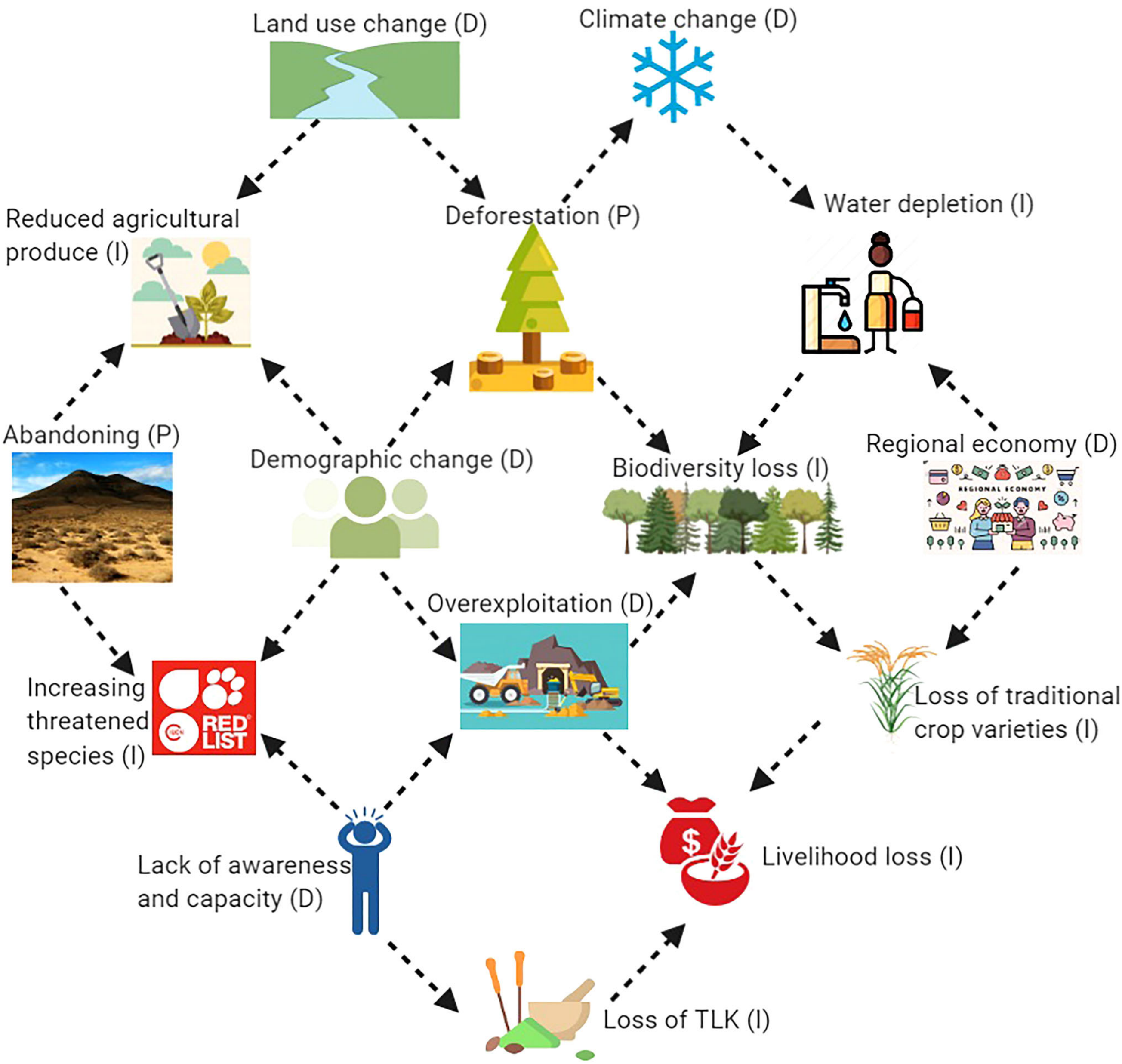

Fig. 7 Linkages between drivers, pressures, and impacts in the IPSI mountain case studies. Note: D: drivers, P: pressures, I: impact

traditional land use, resulting in subsequent loss of livelihoods and at the same time affecting mindset (a pressure) in some of the study SES. Similarly, lack of awareness enhances two other pressures—land abandonment and unsustainable agriculture.

The responses in the IPSI case studies were aimed at dealing with the drivers or the impacts, or both. Since drivers induce pressures, those focusing on drivers also helped in curbing the resultant pressures. Although responses can intervene in the loops of drivers and impacts, their targeting depends on the nature of the response. Within the IPSI case studies, 54% of the responses are targeted at reducing the impacts, while 46% were aimed at drivers of change (Fig. 8). However, due to the complexity of the system, tackling just one driver may or may not solve the problem. The responses in IPSI case studies were suited to the particular social–ecological dynamics of the region and community needs, which in turn made them more suited for tackling specific drivers, pressures, and impacts.

From among the responses, economic, technological, and cognitive responses were geared toward addressing the impacts, such as agricultural sustainability, market access, and livelihood loss. Legal, and social and behavioral responses engage the community in addressing the issues that may not necessarily resolve immediate concern but can

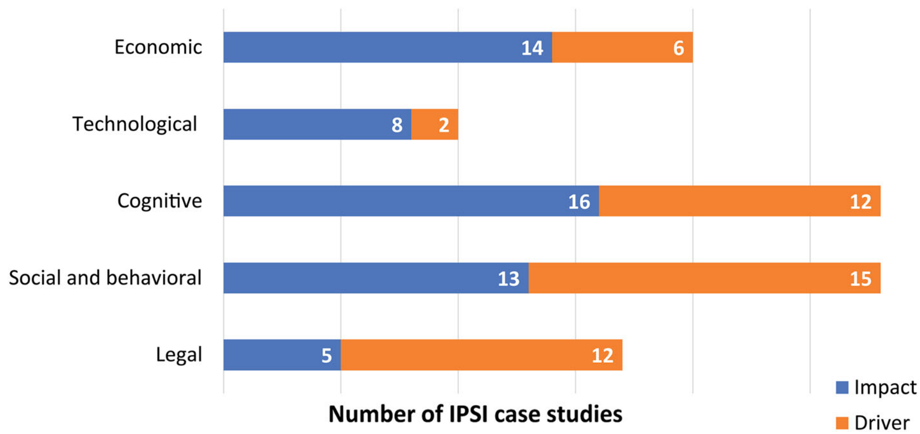

Fig. 8 Targets of responses in the IPSI mountain case studies

have long-term effects on a broader scale, such as overexploitation, climate change adaptation, and land use change.

Lessons learned from IPSI case studies

When looking at the knowledge synthesis outlined in the previous sections, it is possible to make four interconnected critical observations. First, there are four major global drivers that are mediating change in most of the IPSI mountain SES, namely, overexploitation, land use change, demographic change and regional economy (see "Drivers"). These drivers are interconnected and further intersect with other drivers, having major implications for outmigration in mountain areas in both developed and developing countries (see also Fig. 7). This makes clear that both social and ecological dynamics should be taken into account when designing appropriate responses to cope with the change in mountain SES.

Second, despite some similarities across different regions, the drivers, impacts, and pressures (and thus the responses) can vary widely between mountain SES. This implies that one-size-fits-all approaches would most likely not be appropriate or even possible when seeking to mitigate or cope with change in mountain SES. This is evident in Table 2 that summarizes the different approaches identified across the IPSI case studies, alongside the proposed actions and pathways to achieve sustainability outlined in the IPBES Global Assessment Report (IPBES 2019b). In this sense, tailor-made approaches could be more appropriate, even when it comes to inclusive governance, rural–urban connectivity, community empowerment, protection of TLK, and the creation of markets for local produce.

Third, a combination of response options (rather than single responses) could possibly help the mountain communities in coping better with socio-economic change. This is because change can be a multi-dimensional process with multiple interacting drivers, pressures and impacts as outlined above. One example is that customary laws may be quite effective in some mountain regions, while a combination of national and local legislation could further help curb the external influences of extractive industries. Literature from Himalayan region shows that local customary laws based on TLK are more adapted to specific local circumstances than conservation legislation (Pant 2002), but also that local government bodies and self-governance of forests could facilitate the achievement of conservation goals (Mukherjee 2003; Negi et al. 2012).

Fourth, the examples from the IPSI case studies show not only the great potential of community-based approaches anchored on community engagement and TLK, but also indicate possible methods for effective engagement and TLK mobilization. Indeed, the large prevalence of cognitive, social and behavioral responses in IPSI cases suggests that local communities are key elements of responses to change in mountain SES (Table 1). On many occasions, the involvement of local communities in IPSI cases is anchored on innovative practices. It relies on clarifying the perceptions of local communities and stakeholders of the threat of degradation on the one hand and common benefits of sustainable management on the other (Subramanian et al. 2018).

Overall, the IPSI case studies outlined in this paper establish that community engagement is highly valuable for the development and implementation of community-based interventions in mountain SES. This would reasonably lead to the argument that local communities should be mainstreamed into conservation and sustainability planning in mountain SES through strengthening community engagement. This would make planning processes more inclusive by empowering communities through raising awareness about the value of their resources and preparing them for local-level decision-making.

The academic literature reinforces the above findings from the IPSI cases. Community-based approaches have been found to be instrumental for poverty alleviation, biodiversity conservation, and climate resilience in mountain landscapes (IIED 2016). For example, the IPCC SROCC suggests that climate adaptation efforts have benefited from the inclusion of TLK in the mountain regions (Hock et al. 2019). Similarly, biodiversity conservation based on community participation and ownership has been effective in some mountain regions, according to Sharma (2016), while meaningfully integrating their TLK could also enhance their adaptive capacity (Ingty 2017). There is evidence that community engagement has added value in conservation efforts in different mountain regions. For example, the socio-economic benefits of community engagement in conservation efforts outweighed the costs, as witnessed in Nepal's Annapurna Conservation Area (Bajracharya et al. 2006). Other examples include (a) the close linkage between cultural values and diversity, with biodiversity conservation in parts of the Himalayas (Negi 2010) and the Andes (Sarmiento and Cotacachi 2019); (b) the mobilization of TLK and related innovations and practices for biodiversity conservation in Morocco's Mediterranean mountains (UNDP 2019) and Nepal (Zurick 1990); and (c) the close collaboration involving local communities to advance biosystematics, species recovery, habitat restoration and maintenance of traditional livelihoods in Mexico (Wilder et al. 2016). In this sense, failure to foster community engagement could lead to a suboptimal outcome of development and conservation efforts (Imperiale and Vanclay 2016).

However, arguably the engagement of these communities as custodians of mountain SES is fundamentally different from the mechanism whereby authorities designate (through national legislation and other regulatory instruments) areas to be officially 'protected', constraining the use of natural resources (Jacobs 2021). Accordingly, when implementing such regulations, the needs and values of local communities become relevant, which also vary based on different regional social-ecological characteristics of mountain landscapes (Schirpke et al. 2021), including local culture and tradition.

Further to these evidences from the literature, international policy frameworks have also begun to reflect on the need to include indigenous and local communities in both biodiversity conservation and climate change mitigation and adaptation efforts (UNFCCC 2014; CBD 2019a). There have been efforts to mainstream communities in conservation efforts in mountains regions (Phuntsho et al. 2012; Makino et al. 2019) and in the development and operationalization of indicators related to TLK in the Post-2020 Global Biodiversity Framework (CBD 2021). Engagement of indigenous and local communities is being recognized as a potential pathway to transformative change (IPBES 2019b; Nishi et al. 2021) and it is also consistent with the ecosystem-based approaches promoted by the CBD (CBD 2019b) and UNFCCC (UNFCCC 2011).

RECOMMENDATIONS, LIMITATIONS, AND FUTURE STEPS

Based on the findings outlined in the previous sections and mindful of the large variability in the environmental and socio-economic characteristics of the IPSI mountain SES, we can identify four major recommendations.

First, the diversification of local produce and the creation of markets would go a long way toward linking better local communities in mountain SES with other areas. Possible pathways to achieve this would be developing local entrepreneurship by capitalizing on local practices but ensuring their connections to the broader market. Increasing social cohesion in small mountain villages, training local communities in product marketing, facilitating the engagement of the private sector stakeholders, and fostering access to online market platforms could enhance marketing opportunities for mountain products. Beyond improving market opportunities, the above could also improve benefit-sharing with local communities, possibly reducing incentives for illegal extraction or smuggling of marketable products.

Second, there should be endogenous efforts to diversify the livelihoods of mountain communities beyond ecosystem-based livelihoods linked to agriculture, livestock and forestry, so as to hedge the risks of encountering the external pressures. For example, by leveraging the esthetic value and recreational potential of mountain landscapes, it might be possible to increase tourism potential, which could offer alternative livelihoods for local communities in mountain SES. While tourism was viewed as a pressure in IPSI case studies, efforts could seek to transform it more toward an opportunity, especially by encouraging community-based tourism. This could possibly discourage deforestation and unsustainable agricultural practices.

Third, local mountain communities should be encouraged to participate in the monitoring and evaluation (M&E) of project interventions. This could not only solve data deficiencies in mountain areas but could also improve the quality of the data by mobilizing TLK. This has been achieved in some IPSI cases by improving the capacity of communities and making them direct stakeholders in project interventions.

Fourth, the rich biological and cultural diversity encountered in many mountain SES calls for the need to develop biodiversity and TLK registers. The documentation should serve as means of improving community participation and restoring lost or dying TLK.

Despite the broad scope and insights into community-based initiatives across many mountain SES, this study has some limitations. First, IPSI case studies and similar literature focuses on socio-ecological production landscapes and human–nature interactions, preventing insights from more urbanized mountain landscapes, where local communities are less dependent on traditional ecosystem-based livelihoods.

Second, it was not possible to include the 'State' dimension in the DPSIR framework because most of the underlying IPSI studies have either not monitored the status and trends of the SES/landscape or are not comparable between cases (e.g., in terms of methods, variables, visualization). Although this omission reduces to some extent our ability to provide a comprehensive picture, we believe that the findings can provide a good understanding of the main dynamics in mountain SES and possible response options.

Third, as discussed throughout this paper, formal institutions associated with different government levels can play a major role in mountain SES change. Although we have identified such institutions as drivers, pressures, impacts, and responses, it was not possible to comprehensively analyze their role. Future studies should seek to link mountain SES change within and across different institutional settings.

CONCLUSION

The study shows that many mountain SES experience change through overexploitation, land use change, and land abandonment. These portray disturbing possibilities for mountain SES, whose vulnerability to ecosystem services degradation, biodiversity loss, and TLK loss could be compounded by climate change.

It is possible to restore or at least stop their further degradation through appropriate responses. While cognitive responses are promising for tackling impacts, social and behavioral responses have been shown to help adapt or weaken the drivers of change in mountain SES. Both these types of responses heavily rely on community engagement, as the studied mountain SES were mostly managed by mountain communities that depended primarily on ecosystem-based livelihoods. Responses were often tailor-made, as while the type of risks is often similar between mountain SES, their level and underlying mechanisms substantially differed, due to their various cultural, institutional, socio-economic, and ecological contexts. Depending on the contexts, the responses focused on awareness generation, inclusive governance, community empowerment, creation of local markets, and conservation and documentation of traditional practices and TLK.

Overall, this study reaffirms the need for community-based approaches in mountain SES. However, rather than only broadly suggesting inclusion, it identifies some good practices that were successfully implemented in the mountain regions. These insights can be particularly relevant in international processes that seek to further the agenda of indigenous and local community engagement for effective conservation (including in the post-2020 Global Biodiversity Framework) and inclusive resource management to achieve SDG Goal 15.4.

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